

# Chemical Constituents and Oxidative Potential of Fine Particulate Matter in a Cannabis Consumption Lounge: A Case Study

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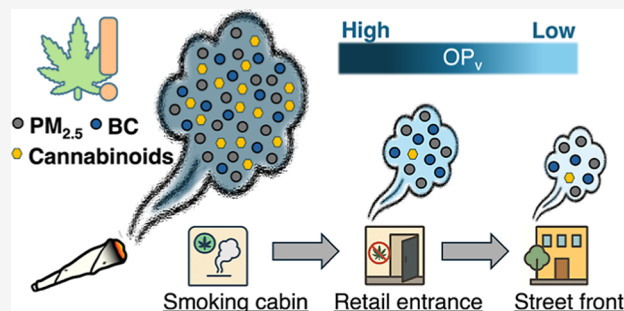
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Supporting Information

**ABSTRACT:** Cannabis consumption lounges represent an emerging indoor microenvironment where secondhand cannabis exposure may pose potential health risks. However, understanding of particle composition and oxidative potential (OP) in these settings remains limited. In this case study, we quantified  $PM_{2.5}$ , black carbon (BC), metals, cannabinoids, and OP in a cannabis consumption lounge and assessed spatial variability across three sampling locations: the smoking cabin, retail entrance, and street front. Mean ( $\pm$ SD)  $PM_{2.5}$  concentrations during busy hours (12 pm–10 pm) reached 92 ( $\pm$ 100)  $\mu\text{g}/\text{m}^3$  in the smoking cabin. Weekly mean  $PM_{2.5}$  concentrations were 63 ( $\pm$ 3.3)  $\mu\text{g}/\text{m}^3$  in the smoking cabin and decreased by 62% and 79% at the entrance and street-front, respectively. BC averaged 11.0 ( $\pm$ 1.8)  $\mu\text{g}/\text{m}^3$  in the smoking cabin and decreased by 76% and 87%. In contrast, total cannabinoids reached 1560 ( $\pm$ 580)  $\text{ng}/\text{m}^3$  in the smoking cabin but decreased more sharply by 98% and 99%. OP metrics showed assay-dependent spatial patterns:  $OP_v^{\text{OH}}$  decreased by 46% and 64%, whereas  $OP_v^{\text{DTT}}$  did not follow the same monotonic decrease. These findings suggest that chemical constituents exhibited distinct spatial behaviors and were not fully confined to the smoking cabin, providing exploratory evidence to inform future engineering controls and regulatory guidance for cannabis consumption lounges.

**KEYWORDS:** black carbon, cannabinoids, fine particulate matter ( $PM_{2.5}$ ), indoor air, metals, oxidative potential



## 1. INTRODUCTION

The cannabis industry has grown rapidly in recent decades, driven by the legalization of pro-cannabis laws in the United States. As of March 2026, 24 states and the District of Columbia allow recreational use of cannabis.<sup>1</sup> Recent studies have shown that more than half of the U.S. population reported ever using cannabis, with 17.7 million individuals identified as daily or near-daily cannabis users.<sup>2</sup> The cannabis market is expected to expand from \$13 billion in 2021 to \$80 billion by 2030, reflecting a compound annual growth rate of 25.5%.<sup>3</sup> In response to the growing cannabis market and user prevalence, cannabis businesses such as dispensaries and consumption lounges have emerged as public spaces where customers can purchase and legally consume cannabis indoors, respectively.<sup>4</sup> As a result, critical concerns have been raised for cannabis businesses due to the environmental impact and potential health risks associated with exposure to secondhand cannabis aerosols in indoor environments.<sup>5,6</sup>

Recent studies on indoor secondhand cannabis emissions have found high concentrations of fine particles ( $PM_{2.5}$ , particulate matter with aerodynamic diameter  $\leq 2.5 \mu\text{m}$ ).<sup>7,8</sup> The reported peak  $PM_{2.5}$  concentrations in residential and public settings often reached over 1000  $\mu\text{g}/\text{m}^3$  during active cannabis use.<sup>9–11</sup> More specifically, our previous study

conducted in a cannabis consumption lounge has found peak  $PM_{2.5}$  concentrations over 1600  $\mu\text{g}/\text{m}^3$  during busy afternoon hours in a smoking cabin, and the mean concentration was more than 20 times higher than that observed overnight.<sup>10</sup> Exposure to  $PM_{2.5}$  has been associated with adverse health effects,<sup>12</sup> and evidence from long-term epidemiological studies further suggested nonthreshold dose-response relationships between  $PM_{2.5}$  exposure and cardiovascular mortality.<sup>13,14</sup>  $PM_{2.5}$  can penetrate into the human respiratory system and facilitate the formation of reactive oxygen species (ROS) through redox-activities or inflammatory responses.<sup>15–17</sup> The accumulation of ROS contributes to oxidative stress, an imbalance between ROS production and antioxidant defense mechanisms, which has been associated with systemic inflammation, respiratory malfunctioning, and cardiopulmonary symptoms.<sup>18–20</sup>

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**Table 1. Characteristics of the Recruited Cannabis Businesses<sup>a</sup>**

| recruited shops             | location       | volume (m <sup>3</sup> ) | smoking policy | ventilation type    | AER (h <sup>-1</sup> ) | temperature (°C) | RH (%)    |
|-----------------------------|----------------|--------------------------|----------------|---------------------|------------------------|------------------|-----------|
| Cannabis dispensary         | West Hollywood | 360                      | Not allowed    | Central A/C         | 0.6                    | 26 (0.9)         | 30 (2.0)  |
| Blend shop                  | West Hollywood | 180                      | Allowed        | Natural ventilation | 1.5                    | 21 (4.0)         | 44 (9.8)  |
| Cannabis consumption lounge | West Hollywood | Cabin: 150               | Allowed        | Wall A/C & Purifier | 7.7                    | 27 (1.0)         | 25 (7.7)  |
|                             |                | Retail: 900              | Not allowed    | Wall A/C            | 0.7                    | 23 (2.0)         | 31 (11.1) |

<sup>a</sup>Values for temperature and RH are presented as mean (SD).

Although the elevated PM<sub>2.5</sub> concentrations provide an important foundation for assessing exposures related to cannabis use, particle mass concentration alone is insufficient to characterize the potential toxicity and health implications of secondhand cannabis emissions. Aerosols generated through cannabis use contain a distinct mixture of combustion-related carbonaceous particles, metals originating from plant material or vaping devices, and cannabinoids such as tetrahydrocannabinol (THC) and cannabidiol (CBD), making characterization of PM<sub>2.5</sub> constituents necessary for understanding cannabis-specific indoor exposures.<sup>21,22</sup>

Among these constituents, black carbon (BC) represents an important PM<sub>2.5</sub> component, primarily generated through combustion processes.<sup>23</sup> BC has been shown to induce oxidative stress due to its surface reactivity and capacity to carry toxic compounds,<sup>24</sup> and ability to increase the activity of redox-active metals.<sup>25,26</sup> A recent laboratory study measured BC concentrations from conventional tobacco cigarette smoking (i.e., burn/incinerate) and found mean BC concentration during active smoke at 2.3 μg/m<sup>3</sup>.<sup>27</sup> Another study compared conventional and heated tobacco smoking, reporting mean BC concentrations of 13.2 and 1.2 μg/m<sup>3</sup>, respectively.<sup>28</sup> BC measurements were incorporated in this study to evaluate combustion-related components of secondhand cannabis aerosols.

Metals are another important class of inorganic PM<sub>2.5</sub> constituents that may contribute to the generation of ROS and associated health effects.<sup>29,30</sup> Studies have assessed metal composition in tobacco smoke and found multiple metal species, including copper (Cu), chromium (Cr), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn).<sup>31</sup> These metals may originate through soil uptake and combustion-related processes that contribute to the toxicity effects of secondhand tobacco smoke.<sup>32</sup> Metals such as Cr, Ni, and Pb are of concern because inhalation exposure to metal-containing particles has been associated with respiratory, neurological, and carcinogenic effects.<sup>33,34</sup> Cannabis plants, particularly hemp (*cannabis sativa* L.), have also been known to accumulate metals from soil.<sup>35</sup> Menezes et al.<sup>36</sup> reported that processed hemp seeds contain magnesium (Mg), potassium (K), phosphorus (P), Fe, Zn, and Cu, with concentrations varying by processing method and product type. Nevertheless, there is currently a lack of studies on metal concentrations in secondhand cannabis aerosols.

PM<sub>2.5</sub> associated with secondhand cannabis emissions may also contain cannabis-specific organic chemicals, such as THC and CBD,<sup>37</sup> which are typical cannabinoids found in cannabis plants and extracts.<sup>38–40</sup> Delta-9 THC (Δ<sup>9</sup>-THC) is a major chemical compound that is responsible for the primary psychoactive effects of cannabis, including acute alterations in cognition, psychomotor performance, and mood.<sup>38,41</sup> CBD, on the other hand, is generally considered less psychoactive than THC and has been associated with cognitive impairment, sedative effects, and neural intoxication.<sup>42–44</sup> In addition to

being analyzed individually, THC and CBD were also combined and reported as total cannabinoids in this study to better represent overall cannabinoid exposure in secondhand cannabis aerosols. Previous study sampled airborne THC and CBD in a cannabis dispensary and detected concentrations of THC and CBD of 79 μg/m<sup>3</sup> and 7.2 μg/m<sup>3</sup>, respectively.<sup>7</sup> Another study quantified surface contamination due to cannabis smoke and vape in a laboratory with Δ<sup>9</sup>-THC concentrations ranging from 0.35 μg/m<sup>2</sup> to 4.9 μg/m<sup>2</sup>.<sup>45</sup> However, this study was conducted in a highly ventilated experimental room under controlled emission protocol. To date, studies focusing on the concentrations of indoor cannabinoids are extremely limited, and yet, no data has been published assessing secondhand cannabinoid concentrations in a public consumption lounge setting with unrestricted cannabis use.

Given the limited understanding of the chemical composition of PM<sub>2.5</sub> associated with secondhand cannabis emissions, this study aims to characterize PM<sub>2.5</sub> and selected constituents (i.e., BC, metals, and cannabinoids including THC and CBD) in the indoor environments of cannabis consumption lounge. To provide further insights on the oxidative stress, we used acellular assays, including dithiothreitol (DTT)<sup>46</sup> and the hydroxyl radical (OH) assay using surrogate lung fluid (SLF),<sup>47</sup> to assess the oxidative potential (OP).<sup>48</sup> To date, limited studies have systematically evaluated the OP of secondhand cannabis aerosols. This knowledge gap is particularly critical in cannabis consumption lounges, where high concentrations of PM<sub>2.5</sub> may affect both employees and customers. Therefore, the objective of this study is to quantitatively characterize secondhand cannabis-related PM<sub>2.5</sub>, BC, metals, cannabinoids, and OP in a cannabis consumption lounge, evaluate spatial variability within and beyond the smoking cabin, and inform future evaluation of mitigation control strategies in high-exposure indoor environments.

## 2. MATERIALS AND METHODS

### 2.1. Study Sites

All businesses were identified through online search ([Yelp.com](https://www.yelp.com) and [Google.com](https://www.google.com)) using keywords “cannabis shop”, “dispensary”, “smoke shop”, and “consumption lounge”. Recruitment involved flyer distribution, phone calls, and in-person visits. As the recruited smoke shop allows both tobacco and cannabis use, we refer to it as “blend shop”. Due to the limited number of available cannabis consumption lounges, one lounge in City of West Hollywood was recruited first. Cannabis dispensaries and blend shops were subsequently selected within a five-mile radius to minimize regional variation and were located away from major particle sources (e.g., restaurants, freeways, gas stations, industrial facilities).<sup>49</sup> The three recruited businesses enabled comparative evaluation of particle concentrations under different indoor smoking policies and product types.<sup>50</sup> Detailed characteristics, including volume, smoking policy, ventilation type, air exchange rate (AER), temperature, and RH, are summarized in Table 1. The analyses of BC, cannabinoids, and OP

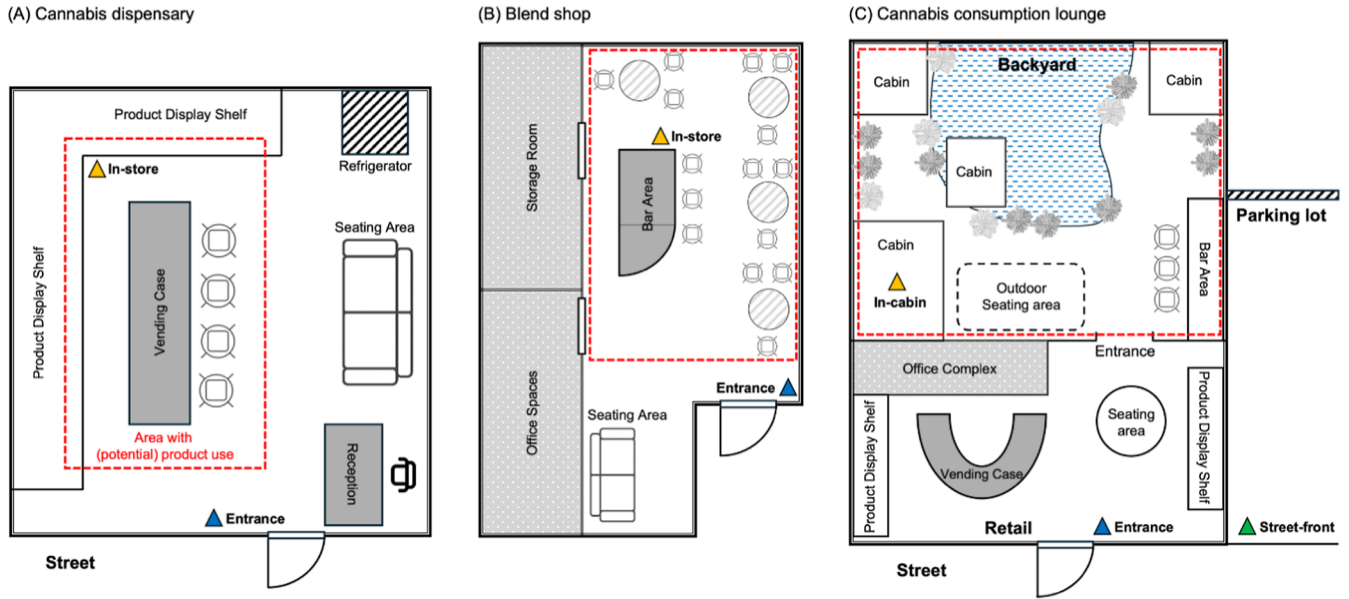


**Figure 1.** Schematic diagram of sampling locations and floor design of the tested cannabis dispensary, blend shop, and cannabis consumption lounge. Red dashed area represents areas with potential use of cannabis products, representing potential emission hotspot.

**Table 2.** Summary of Sampling Devices and Purposes in Recruited Cannabis Businesses

| business                    | sampling locations | sampling period             | sampling instrument | type of samples              | number of samples |
|-----------------------------|--------------------|-----------------------------|---------------------|------------------------------|-------------------|
| Cannabis dispensary         | In-store           | Mar 26th—Apr 2nd, 2024      | PurpleAir           | Continuous PM <sub>2.5</sub> | -                 |
|                             | Entrance           |                             | UPAS                | Metal                        | 1 (PTFE)          |
| Blend shop                  | In-store           | Apr 22nd—Apr 29th, 2024     | PurpleAir           | Continuous PM <sub>2.5</sub> | -                 |
|                             | Entrance           |                             | UPAS                | Metal                        | 1 (PTFE)          |
| Cannabis consumption lounge | In-cabin           | Mar 26th—Apr 2nd, 2024      | PurpleAir           | Continuous PM <sub>2.5</sub> | -                 |
|                             |                    |                             | UPAS                | Metal                        | 1 (PTFE)          |
|                             |                    | Dec 9th, 2024—Jan 7th, 2025 | UPAS                | Cannabinoids                 | 3 (microfiber)    |
|                             |                    |                             | UPAS                | BC & OP                      | 3 (PTFE)          |
|                             | Entrance           | Mar 26th—Apr 2nd, 2024      | PurpleAir           | Continuous PM <sub>2.5</sub> | -                 |
|                             |                    | Dec 9th, 2024—Jan 7th, 2025 | UPAS                | Cannabinoids                 | 3 (microfiber)    |
|                             |                    |                             | UPAS                | BC & OP                      | 3 (PTFE)          |
|                             | Street-front       | Dec 9th, 2024—Jan 7th, 2025 | UPAS                | Cannabinoids                 | 3 (microfiber)    |
|                             |                    |                             | UPAS                | BC & OP                      | 3 (PTFE)          |

were focused only on the cannabis consumption lounge as it has been shown to be emission hotspot.<sup>10</sup>

2.2. Sampling Locations

The study was conducted between March 26th, 2024, and January seventh, 2025, based on site access and scheduling availability. Air monitoring and sampling were conducted in all three cannabis businesses. A total of two locations were selected for the single-unit cannabis dispensary and blend shop: (1) at inside-business area (in-store), such as the display shelf and bar areas in the cannabis dispensary and blend shop, respectively; and (2) at the entrance (Figure 1A,B). Three locations were selected in the multiunit cannabis consumption lounge: the first location was at inside-smoking cabin (in-cabin), and the second location was at the entrance of retail area. To investigate particle transport, we selected the street-front area outdoors as the third sampling location (Figure 1C). The inclusion of three locations at the cannabis consumption lounge helps characterize exposure differences within and outside the more complex architectural settings compared to the cannabis dispensary and blend shop.

2.3. Sample Collection & Analysis

**2.3.1. Measurement of Continuous PM<sub>2.5</sub> Concentrations.** The PurpleAir PA-II sensors (PurpleAir Inc., Draper, UT) were used for PM<sub>2.5</sub> monitoring at the three cannabis businesses. The PurpleAir sensors were placed at 1.5 to 1.8 m above the ground at the selected locations. Upon completion of air monitoring, we retrieved the micro-SD card and downloaded the sampling log, which contained information on particle mass concentrations and meteorological parameters such as temperature and relative humidity. Air monitoring was conducted for a continuous one-week period within each business. The data-logging interval for PurpleAir sensors was at 2 min, which provided up to over 10,080 total data points per business and over 30,000 data points for the three cannabis businesses combined.

**2.3.2. Filter Collection and Analysis.** Filter samples were collected using Ultrasonic Personal Aerosol Samplers (UPAS v2.1 PLUS, Access Sensor Technologies, Fort Collins, CO, USA) with a 2.5 μm cutoff. The performance of the UPAS monitors has been validated in both laboratory and field studies, demonstrating results consistent with gold standard instruments such as the Harvard Impactor and the Mesa Laboratories/BGI Triplex Cyclone.<sup>51–53</sup> The sampling flow rate for the UPAS was set at 1 L/min using the “AST

UPAS" mobile application (Version 1.0.4, Build 1.0.1) and the sampling duration was 1 week. Air sampling lasted for 1 week for metal analysis using 37 mm polytetrafluoroethylene (PTFE) filters (Cytiva R2PJ037, 2.0  $\mu\text{m}$  pore size), 3 weeks for BC and OP analyses using 37 mm PTFE filters, and 3 weeks for cannabinoids using 37 mm borosilicate glass microfiber filters (Cytiva Pallflex Emfab air monitoring filters, TX40HI20WW). Table 2 summarizes the sampling periods, type of collections, and number of samples at each cannabis business. The mass of  $\text{PM}_{2.5}$  on collected filters was measured gravimetrically using a microbalance (Model MX5, Mettler Toledo Inc., Columbus, OH, USA) with 1  $\mu\text{g}$  resolution (see more details in Supporting Information).

**2.3.3. BC Analysis.** We estimated BC collected onto PTFE filters (Table 2) using the dual-wavelength optical transmissometer OT21 (Magee Scientific). The instrument measures optical absorption at 370 and 880 nm. Optically derived BC concentrations were calculated from absorption 880 nm, and the Ångström exponent was calculated from the absorption at 370 nm to assess the contribution of brown carbon. A detailed description of the loading corrections for the BC measurements is based on Paulson et al.<sup>54</sup> and can be found in the Supporting Information.

**2.3.4. Metal Concentration Analysis.** For metal analysis, the PTFE filters collected through UPAS (Table 2) were removed from the support rings, and the collected particles were dissolved using a mixed-acid, microwave-assisted bomb digestion. The digestion process was performed in a Milestone Ethos Easy microwave with an SK15 pressurized rotor and micro vials, using a solution consisting of 1.5 mL of 16 M nitric acid, 0.5 mL of 12 M hydrochloric acid, and 0.1 mL of 28 M hydrofluoric acid. The microwave program included a 25 min ramp-up to 205  $^{\circ}\text{C}$ , followed by a 25 min hold at that temperature. The resulting digests were diluted to 15 mL using ASTM Type 1 reagent water, and then further diluted by a 1:2 ratio for analysis using sector field inductively coupled plasma mass spectrometry (SF-ICP-MS) (Thermo-Finnigan Element XR). The metal analysis provided a panel of 55 metal species, from which we selected seven metal species (i.e., Cr, Cu, Fe, Mn, Ni, Pb, Zn) for this study based on: (1) the metals found in cannabis plants and extracts (Table S1), and (2) their detection from tobacco studies (Table S2). All selected metals except Ni had concentrations over the limit of detection (LOD), and thus, the reported concentrations for Ni were substituted using one-half (1/2) of LOD for descriptive analysis.<sup>55</sup>

**2.3.5. Airborne Cannabinoid Analysis.** Methanol was used as a solvent to extract cannabinoids (THC and CBN) from particles collected on the 37 mm borosilicate glass microfiber filters (Table 2). Known amounts of methanol completely covered each filter specimen inside the vial, which was placed inside an ultrasonic bath for 30 min. Then, the extract was injected to a gas chromatography–mass spectrometry (GC/MS, Agilent 5977), and analyte concentration was determined in splitless mode, with oven temperature ramping over a range of 30–310  $^{\circ}\text{C}$ . The calibration range was between 40  $\text{pg}/\mu\text{L}$  and 50  $\text{ng}/\mu\text{L}$ . In preliminary tests, a second aliquot of clean methanol was added to the vial containing the extracted filter specimen and was sonicated for another 30 min. The supernatant was removed and injected into GC/MS and analyzed for cannabinoid concentration. The second extraction contained <10% of the total concentration, and thus, only one extraction was used for most sample extractions.

For cannabinoid analysis, filters were collected as week-long integrated samples to ensure sufficient mass loading and analytical sensitivity. Extended sampling durations may allow partial chemical transformation of collected cannabinoids, including oxidation of THC to CBN. Therefore, THC and CBN were reported both individually and as their sum (THC + CBN) to provide an approximate integrated indicator of measured cannabinoid content, as losses, degradation, volatilization, breakthrough, and storage artifacts may occur during extended sampling.

**2.3.6. OP Analysis Using OH and DTT Assays.** After optical measurements of BC, the PTFE filters were cut into two-halves using ceramic scissors for the OH and the DTT assay, respectively. Each filter half was incubated in surrogate lung fluid (SLF) containing the

terephthalate OH probe for the OH assay and in phosphate buffer with DTT for the DTT assay. The OP measured in this study primarily reflects the response to soluble  $\text{PM}_{2.5}$  components but may also capture some reactions occurring on the surfaces of insoluble components.

The OH assay, as detailed by Gonzalez et al.,<sup>47</sup> uses terephthalate to detect OH radical formation in surrogate lung fluid (SLF) at 37  $^{\circ}\text{C}$ , over a 90 min incubation period. The fluorescence of 2-hydroxyterephthalate was measured at an excitation/emission ( $\lambda_{\text{ex}}/\lambda_{\text{em}}$ ) wavelength of 320/420 nm using a fluorescence spectrometer (Scinco, Korea). The incubation solution volume was adjusted by proportionally varying the extraction volume based on the total  $\text{PM}_{2.5}$  mass collected on each filter, such that a target extract concentration of 25  $\mu\text{g}/\text{mL}$  was achieved.

The DTT assay evaluates the degradation of 100  $\mu\text{M}$  DTT in phosphate buffer during a 32 min incubation at 37  $^{\circ}\text{C}$ . Samples were incubated with a  $\text{PM}_{2.5}$  concentration (solution) of 10  $\mu\text{g}/\text{mL}$ . DTT levels were quantified by reacting it with dithiobis nitrobenzoic acid, resulting in the formation of 2-nitro-5-thiobenzoic acid.<sup>56</sup> More details on the OH and DTT assays are available in Supporting Information.

## 2.4. Quality Assurance and Quality Control

All measurements adhered to strict QA/QC protocols. PurpleAir sensor data were processed using the ALT CF3 algorithm (also known as ALT cf. = 3) for the analysis of continuous  $\text{PM}_{2.5}$  concentrations.<sup>57,58</sup> PurpleAir sensor data were compared with concurrent UPAS gravimetric  $\text{PM}_{2.5}$  measurements. Weekly average  $\text{PM}_{2.5}$  concentrations derived using the ALT CF3 correction factor agreed within 7–10% of the corresponding UPAS measurements, supporting the use of PurpleAir sensors for time-resolved  $\text{PM}_{2.5}$  monitoring (Table S3).

UPAS monitors were cleaned and flow-checked before and after field deployment, with field and laboratory blanks collected to confirm mass accuracy within U.S. EPA acceptance criteria. All filters were conditioned under controlled temperature ( $20 \pm 1$   $^{\circ}\text{C}$ ) and humidity ( $35 \pm 1\%$ ) and weighed in triplicate after static neutralization. For oxidative potential assays (OH and DTT), all glassware and reagents were acid-cleaned and metal-free. Each assay included calibration standards, blanks, and triplicate measurements with low blank responses. More details on QA/QC are available in Supporting Information.

## 2.5. Data Analysis

A 24 h day was categorized into three busyness levels (busy: 12–10 pm; less busy: 9 am to 12 pm; and overnight: 10 pm to 9 am next day) based on our established criteria for subsequent analysis on  $\text{PM}_{2.5}$  data collected through PurpleAir PA-II sensors.<sup>10</sup> Summary statistics of  $\text{PM}_{2.5}$  concentrations (mean  $\pm$  SD) were calculated. Time series plots were created to visualize the concentrations of  $\text{PM}_{2.5}$  at different cannabis businesses. Box plots were generated to compare  $\text{PM}_{2.5}$  concentrations in different cannabis businesses and OP levels at different sampling locations in the cannabis consumption lounge.

To provide a descriptive estimate of business-hour contributions for integrated metal samples, an area under the curve (AUC) approach was applied to time-resolved  $\text{PM}_{2.5}$  data using the trapezoidal integration method.<sup>59</sup> Daily AUCs were calculated for both the full 24 h period and separately for business hours (9:00 am to 10:00 pm) by segmenting the time series curves. Approximately 93.5% of the daily  $\text{PM}_{2.5}$  mass was sampled during business hours, although this period represents only 54.2% of the total daily sampling duration (13 of 24 h). A time-normalization ratio ( $0.935/0.542 = 1.725$ ) was applied to adjust the contribution of metals during business hours (see Supporting Information for details). This  $\text{PM}_{2.5}$ -based adjustment ratio was used only as an approximate time-normalization factor for metals, assuming that metal-containing  $\text{PM}_{2.5}$  followed the temporal pattern of total  $\text{PM}_{2.5}$ .

To evaluate  $\text{PM}_{2.5}$  concentrations observed in the smoking cabin, an emission rate estimation was conducted based on steady-state mass balance assumptions (see Supporting Information 1.6). Measured OH formation rate and DTT loss rate were converted to mass- ( $\text{OP}_{\text{m}}$ ) and

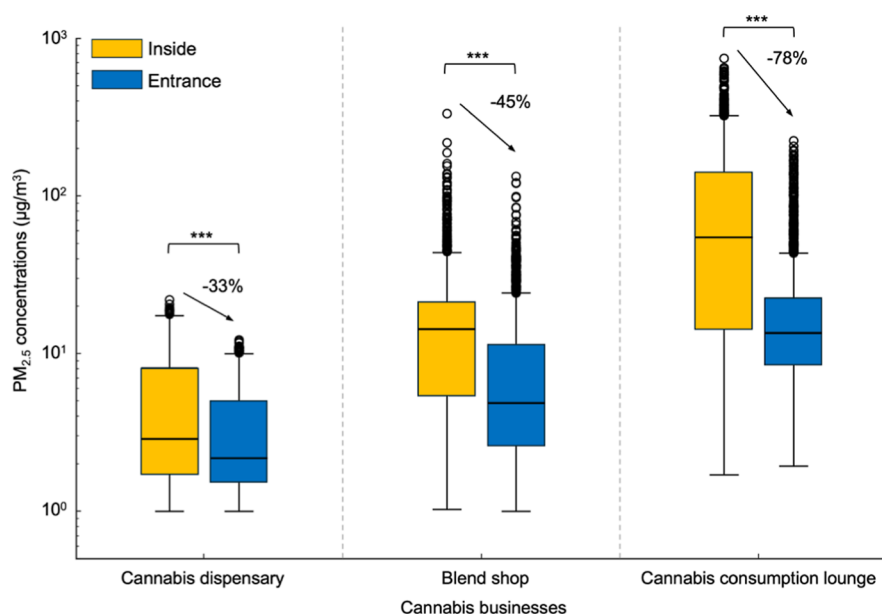


**Figure 2.**  $\text{PM}_{2.5}$  concentrations during busy hours (12–10 pm) at three cannabis businesses. Boxplots in orange and blue represent the inside-business and entrance locations, respectively. Interquartile ranges are shown (25th and 75th percentiles) and outliers within 95 percentiles are included. Black lines within each box represent the mean concentrations. Differences of  $\text{PM}_{2.5}$  concentrations between two locations are compared using Mann–Whitney U test, with two-sided significance level of 0.05 (\*\*\*) ( $p < 0.001$ ). Additional descriptive statistics, including median, IQR, and maximum values, are provided in Table S4.

volume-normalized ( $\text{OP}_v$ ) format prior to analysis. Differences in  $\text{OP}_v$  levels across the three sampling locations in the cannabis consumption lounge were evaluated using one-way ANOVA. Nonparametric Mann–Whitney U tests were applied for pairwise comparisons of  $\text{OP}$  between locations. Linear regression analyses were conducted to examine associations between  $\text{PM}_{2.5}$  and BC against  $\text{OP}$ . Given the limited number of week-long integrated samples, the ANOVA, pairwise, and regression results are treated as exploratory and are intended to describe spatial patterns rather than to support formal statistical inference. All data analyses were performed using Microsoft Excel and RStudio version 1.2.5019.<sup>60</sup>

### 3. RESULTS AND DISCUSSION

#### 3.1. $\text{PM}_{2.5}$ and Metal Concentrations at Three Cannabis Businesses

After 1 week of continuous  $\text{PM}_{2.5}$  monitoring, mean ( $\pm\text{SD}$ ) concentration during busy hours (12 pm–10 pm) reached  $92 (\pm 100) \mu\text{g}/\text{m}^3$  at the in-cabin location of the cannabis consumption lounge, higher than those observed at the in-store locations of the blend shop ( $18 \pm 21 \mu\text{g}/\text{m}^3$ ) and cannabis dispensary ( $4.9 \pm 4.2 \mu\text{g}/\text{m}^3$ ). At the entrance,  $\text{PM}_{2.5}$  concentrations in the cannabis consumption lounge averaged  $21 (\pm 24) \mu\text{g}/\text{m}^3$ , compared with  $10 (\pm 13) \mu\text{g}/\text{m}^3$  in the blend shop and  $3.3 (\pm 2.3) \mu\text{g}/\text{m}^3$  in the dispensary (Figure 2). The higher concentrations observed in the cannabis consumption lounge are consistent with the presence of active indoor cannabis use. However, as the recruited businesses differed in room volume, ventilation, smoking policy, and likely occupancy, the cross-business differences may reflect both particle source strength and removal processes and should be interpreted as descriptive observations rather than direct effects of distinct business types.

Using a simplified steady-state mass balance model, we calculated an order-of-magnitude estimate of  $\text{PM}_{2.5}$  emission rates for the three cannabis businesses. During busy hours, the estimated emission rate in the smoking cabin was approx-

imately  $1.8 \text{ mg}/\text{min}$ , compared with  $0.08 \text{ mg}/\text{min}$  in the blend shop and  $0.02 \text{ mg}/\text{min}$  in the dispensary.

The order-of-magnitude estimates suggest that active cannabis use may contribute to  $\text{PM}_{2.5}$  emissions in the smoking cabin. Ott et al.<sup>61</sup> previously reported  $\text{PM}_{2.5}$  emission rates of approximately  $7.8 \text{ mg}/\text{min}$  for prerolled cannabis joints in a  $43 \text{ m}^3$  residential room with an AER of  $\sim 0.4 \text{ h}^{-1}$ . In comparison, our estimate was derived from a different indoor setting with larger room volume ( $150 \text{ m}^3$ ) and higher AER ( $7.7 \text{ h}^{-1}$ ). On the other hand, the magnitude of the estimated emission rate in the smoking cabin was within the same broad range as that of tobacco cigarette smoking at  $2\text{--}3 \text{ mg}/\text{min}$ .<sup>62,63</sup> However, this comparison should be interpreted cautiously because source type, room volume, ventilation, sampling duration, and experimental conditions differ across studies.

We then measured the concentrations of seven metals (Cr, Cu, Fe, Mn, Ni, Pb, and Zn) from PTFE filters collected at the three cannabis businesses. A time-integrated AUC approach was applied to calculate business-hour (9:00 am to 10:00 pm)  $\text{PM}_{2.5}$  emission relative to that of the full sampling period to adjust for the contribution of active business operations (see Methods 2 and Supporting Information S1.5).<sup>59</sup> Using this adjustment, we found that six of the seven metals (except Zn) showed the highest estimated concentrations in the cannabis consumption lounge (Table S5). This result is consistent with our findings on  $\text{PM}_{2.5}$  concentrations, as unrestricted cannabis use in the cannabis consumption lounge likely results in higher emissions and the accumulation of metals. As this adjustment assumes that metal levels followed the temporal pattern of total  $\text{PM}_{2.5}$ , these values should be interpreted as approximate estimates rather than direct measurements of business-hour metal concentrations.

Besides smoking activities, metals observed in collected cannabis  $\text{PM}_{2.5}$  samples may also derive from delivery devices such as vape devices (e.g., heating coils, vaporizer cartridges), rolling papers, bongs, or even packaging residues. Mallampati

et al.<sup>64</sup> and Meehan-Atrash et al.<sup>21</sup> have shown that when combusted or heated via metallic coils, cannabis leaves and vaping products release metals such as Cr, Cu, Ni, and Pb, either from the plant itself or from the device hardware. Metals such as Cr, Ni, and Pb are of particular concern given their classification as respiratory toxicants and potential carcinogens.<sup>65</sup> For instance, Pb exposure can impair neurological development, cardiovascular function, and kidney health<sup>66</sup> and is particularly hazardous in repeated low-dose exposures.<sup>67</sup> Besides these metals, Mn, while an essential nutrient at trace levels, poses neurotoxic risks when inhaled over prolonged periods.<sup>68,69</sup> The inhalation of metal-containing aerosols poses potential respiratory and neurological risks, especially for employees working in a cannabis consumption lounge.

When compared contextually with studies on metal concentrations from secondhand tobacco smoke, the concentrations in cannabis businesses were at similar or lower levels. For instance, a recent study of waterpipe secondhand smoke reported a Ni concentration of 0.08 ng/m<sup>3</sup>,<sup>70</sup> which is comparable to the concentrations found in cannabis businesses (0.1–0.2 ng/m<sup>3</sup>, Table S5). Nonetheless, a household indoor smoking study reported a total Pb concentration of 21.8 ng/m<sup>3</sup> for residences with smokers,<sup>71</sup> which is more than 20 times higher than our result (0.9 ng/m<sup>3</sup>). Additionally, a study involving 36 cafes<sup>72</sup> reported much higher Cr (24 ng/m<sup>3</sup>) and Ni (35 ng/m<sup>3</sup>) concentrations in secondhand tobacco smoke than our findings (Cr at 1.4 ng/m<sup>3</sup>, Ni at 0.2 ng/m<sup>3</sup>). These large differences can be attributed to variations in sampling protocol. The study of the 36 cafes only sampled for 2 h particularly during active smoking periods,<sup>72</sup> while our study collected samples continuously over a span of a week (168 h) including less busy and overnight periods. Based on our previous research, busier times tend to occur on weekends and become most active in the afternoons.<sup>10</sup> The extended sampling duration and the lack of targeted samplings on active cannabis use increased the total sampled air volume and captured lower exposure periods, which likely contributed to the lower volume-normalized metal concentrations observed in our study.

### 3.2. Concentrations of BC, Cannabinoids, and OP in the Cannabis Consumption Lounge

Given that both PM<sub>2.5</sub> and metal concentrations were higher in the cannabis consumption lounge compared to the dispensary and blend shop, we conducted further analyses in the cannabis consumption lounge to characterize cannabis combustion-related constituents (i.e., BC), organic chemicals of cannabis use (i.e., total cannabinoids, THC and CBN), and OP to better understand the concentrations of chemical components of PM<sub>2.5</sub> associated with secondhand cannabis emissions.

For the cannabis consumption lounge, the mean ( $\pm$ SD) optically derived BC concentration was 11.0 ( $\pm$ 1.8)  $\mu$ g/m<sup>3</sup> in-cabin, 2.7 ( $\pm$ 1.0)  $\mu$ g/m<sup>3</sup> at the entrance, and 1.4 ( $\pm$ 0.8)  $\mu$ g/m<sup>3</sup> at the street-front (Table 3). For comparison, in previous tobacco studies, mean BC concentrations of over 2  $\mu$ g/m<sup>3</sup> have been reported in a laboratory,<sup>27</sup> while a household study targeting active tobacco use reported 13.2  $\mu$ g/m<sup>3</sup>.<sup>28</sup> The BC concentration measured in the smoking cabin (11.0  $\pm$  1.8  $\mu$ g/m<sup>3</sup>) was also higher than BC concentrations reported for in-vehicle settings (2.1–6.1  $\mu$ g/m<sup>3</sup>).<sup>28</sup> Notably, the BC concentration at retail entrance (2.7  $\pm$  1.0  $\mu$ g/m<sup>3</sup>), where smoking is prohibited, was within the range of BC concentrations reported for vehicle cabin tobacco use and

**Table 3. Mean Concentrations, Standard Deviations, and Volume- and Mass-Normalized Values for PM<sub>2.5</sub> Mass Concentrations, BC, Cannabinoid Concentrations, and OP at Different Locations in the Cannabis Consumption Lounge**

| Measurements <sup>a</sup>                                 | In-cabin   | Entrance  | Street-front |
|-----------------------------------------------------------|------------|-----------|--------------|
| PM <sub>2.5</sub> ( $\mu$ g/m <sup>3</sup> )              | 63 (3.3)   | 24 (5.8)  | 13 (7.6)     |
| BC ( $\mu$ g/m <sup>3</sup> )                             | 11.0 (1.8) | 2.7 (1.0) | 1.4 (0.8)    |
| THC (ng/m <sup>3</sup> )                                  | 580 (320)  | <LOD      | <LOD         |
| CBN (ng/m <sup>3</sup> )                                  | 980 (280)  | 33 (29)   | 20 (4.6)     |
| Total cannabinoids (ng/m <sup>3</sup> )                   | 1560 (580) | 33 (29)   | 20 (4.6)     |
| OP <sub>m</sub> <sup>OH</sup> (pmol/min/ $\mu$ g)         | 0.5 (0.1)  | 0.6 (0.1) | 0.6 (0.1)    |
| OP <sub>v</sub> <sup>OH</sup> (pmol/min/m <sup>3</sup> )  | 29 (7.5)   | 16 (6.6)  | 11 (6.4)     |
| OP <sub>m</sub> <sup>DTT</sup> (pmol/min/ $\mu$ g)        | 10 (5.7)   | 2.5 (1.1) | 15 (6.6)     |
| OP <sub>v</sub> <sup>DTT</sup> (pmol/min/m <sup>3</sup> ) | 240 (150)  | 160 (74)  | 210 (14)     |

<sup>a</sup>Measurements were based on week-long integrated filter samples. Total cannabinoids were calculated as THC + CBN; values below LOD were treated as zero. All values are presented as mean (SD).

higher than heated tobacco product (1.2  $\mu$ g/m<sup>3</sup>).<sup>28</sup> These results suggest that active cannabis smoking may contribute to elevated BC concentrations in the smoking cabin, with emission strengths comparable to those from tobacco use. This is further supported by a positive correlation between mass-normalized BC content and PM<sub>2.5</sub> mass concentration (Figure S1), indicating that samples with higher particle mass contained proportionally more BC, consistent with greater contributions from cannabis smoke. However, as the referenced studies differed in sources, sampling duration, and ventilation conditions, these comparisons should be interpreted as contextual references. Optically derived BC may serve as an indicator of combustion-related particle components that can contribute to oxidative activity.<sup>23,24</sup> High BC concentrations observed at both the in-cabin and entrance locations in the cannabis consumption lounge indicate elevated BC exposure for employees and customers, underscoring the need for engineering controls such as negative-pressure rooms or high-efficiency particulate air (HEPA) filtration to mitigate exposures.<sup>73–75</sup>

The concentrations of THC and CBN were quantified from filters collected at three locations at the cannabis consumption lounge. At the in-cabin location, the mean ( $\pm$ SD) concentrations of THC and CBN were 580 ( $\pm$ 320) ng/m<sup>3</sup> and 980 ( $\pm$ 280) ng/m<sup>3</sup>, respectively (Table 3). As an approximate indicator of overall cannabinoid exposure, the total cannabinoids concentration was calculated to be 1560 ( $\pm$ 580) ng/m<sup>3</sup>. At the entrance and street-front, THC was below LOD, while CBN was still detectable (entrance, 33  $\pm$  29 ng/m<sup>3</sup> and street-front, 20  $\pm$  4.6 ng/m<sup>3</sup>, respectively) (Table 3). While total cannabinoids were used to represent overall exposure, individual cannabinoid species (THC and CBN) were compared with previous studies to enable direct comparison with the reported values and to examine potential compositional differences. Wiegand et al.<sup>76</sup> reported THC concentrations between 53 and 330 ng/m<sup>3</sup> during concerts at an open-air football stadium. In comparison, the THC concentration measured in the smoking cabin (580 ng/m<sup>3</sup>) was higher, possibly due to confined indoor spaces of the smoking cabin. Huang et al.<sup>7</sup> found THC and CBN concentrations of 79  $\mu$ g/m<sup>3</sup> and 7.2  $\mu$ g/m<sup>3</sup> in a cannabis business, respectively, which were more than 10 times higher than our results. This is likely because of shorter sampling durations (i.e., 30 min to 1

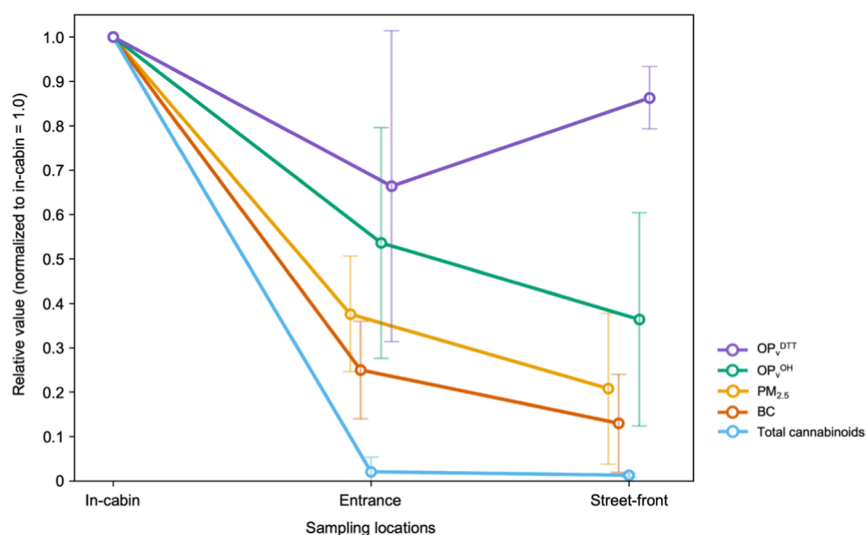


**Figure 3.** Relative changes in  $\text{PM}_{2.5}$ , BC, total cannabinoids,  $\text{OP}_v^{\text{OH}}$ , and  $\text{OP}_v^{\text{DTT}}$ , at different sampling locations compared with the in-cabin location. Brackets show 95% confidence interval for the change relative to the in-cabin location as reference.

h) targeting periods of active cannabis use. Additionally, our results showed higher CBN concentration relative to THC in the smoking cabin, whereas Huang et al. reported higher THC concentration.<sup>7</sup> While variability in THC/CBN content of cannabis products may contribute to these differences, the higher CBN concentrations observed in our study are more likely associated with the extended filter sampling duration (1 week). Previous study measured exhaled breath following cannabis use and identified THC as the primary cannabinoid,<sup>77,78</sup> with CBN not typically detected. Thus, higher CBN concentrations observed in our study likely reflect oxidative transformation of THC to CBN during prolonged sampling.<sup>79</sup>

It should be further noted that all cannabinoid concentrations reported in this study represent time-weighted averages from week-long integrated filter samples and may not fully capture short-term peak exposures during periods of active cannabis use. Real-time  $\text{PM}_{2.5}$  measurements in the smoking cabin indicate large temporal variability, with observed daily peak concentrations on the order of  $\sim 500$ – $750 \mu\text{g}/\text{m}^3$  (Figure S2) compared to the week-long average of  $63 \mu\text{g}/\text{m}^3$  (Table 3), corresponding to peak-to-average ratios of approximately 8–12. If total cannabinoid concentration is scaled proportionally with  $\text{PM}_{2.5}$  based on short-term peaks, total cannabinoid concentrations could be on the order of roughly one magnitude ( $10\times$ ) higher than the time-weighted averages reported, suggesting that the integrated filter-based measurements may substantially underestimate short-term peak cannabinoid exposures in the smoking cabin. However, this estimate assumes that cannabinoids/ $\text{PM}_{2.5}$  ratio remained similar during peak and average periods and should be interpreted cautiously as this ratio may vary. As exposure to cannabinoids has been associated with dose-dependent increases in intoxication, cognitive impairment, and anxiety symptoms,<sup>80,81</sup> our results call for effective control strategy to mitigate potential high cannabinoids exposure in the smoking cabin.

To investigate the oxidative stress of  $\text{PM}_{2.5}$  in the cannabis consumption lounge, we conducted OP analysis on week-long integrated filters collected from three sampling locations. Specifically, mean ( $\pm\text{SD}$ ) volume-normalized  $\text{OP}_v^{\text{OH}}$  at the in-cabin, entrance, and street-front locations were at  $29 (\pm 7.5)$ ,

$16 (\pm 6.6)$ , and  $11 (\pm 6.4) \text{ pmol}/\text{min}/\text{m}^3$ , respectively. In comparison,  $\text{OP}_v^{\text{DTT}}$  were higher overall, at  $240 (\pm 150)$  (in-cabin),  $160 (\pm 74)$  (entrance), and  $210 (\pm 14)$  (street-front)  $\text{pmol}/\text{min}/\text{m}^3$ , respectively (Table 3). Mass-normalized  $\text{OP}_m^{\text{OH}}$  remained relatively consistent across locations ( $0.5 \pm 0.1$ ,  $0.6 \pm 0.1$ , and  $0.6 \pm 0.1 \text{ pmol}/\text{min}/\mu\text{g}$  at in-cabin, entrance, and street-front locations, respectively). In contrast,  $\text{OP}_m^{\text{DTT}}$  showed substantial spatial variability ( $10 \pm 5.7 \text{ pmol}/\text{min}/\mu\text{g}$  in-cabin,  $2.5 \pm 1.1 \text{ pmol}/\text{min}/\mu\text{g}$  at the entrance, and  $15 \pm 6.6 \text{ pmol}/\text{min}/\mu\text{g}$  at the street-front). Statistical comparisons across sampling locations, including one-way ANOVA and pairwise tests, are provided in Figure S3 and Table S6, respectively.

While previous studies have suggested that OH and DTT assays capture distinct yet complementary redox mechanisms, highlighting the need to apply both metrics for a complete assessment of oxidative stress,<sup>56,82,83</sup>  $\text{OP}_v$  is useful for comparing volume-normalized oxidative activity across locations because it reflects oxidative activity per volume of air.<sup>84</sup> Our results show that one-way ANOVA indicated differences in  $\text{OP}_v^{\text{OH}}$  across the three sampling locations (Figure S3), which may reflect a higher potential for oxidative stress in the smoking cabin.<sup>85,86</sup>

Measured OP levels were compared with values reported for other indoor and outdoor microenvironments. The in-cabin  $\text{OP}_v^{\text{DTT}}$  level ( $240 \text{ pmol}/\text{min}/\text{m}^3$ ) is within the range reported for urban ambient environment in the Greater Los Angeles area and below peak values observed in settings with high traffic pollution ( $\sim 750 \text{ pmol}/\text{min}/\text{m}^3$ ).<sup>56</sup> In contrast,  $\text{OP}_v^{\text{OH}}$  measured in the smoking cabin ( $29 \text{ pmol}/\text{min}/\text{m}^3$ ) is comparable to or higher than values commonly reported for urban background environments ( $10$ – $25 \text{ pmol}/\text{min}/\text{m}^3$ ).<sup>56,82</sup> On a mass-normalized basis,  $\text{OP}_m^{\text{DTT}}$  levels in the smoking cabin ( $10 \text{ pmol}/\text{min}/\mu\text{g}$ ) and at the street-front ( $15 \text{ pmol}/\text{min}/\mu\text{g}$ ) are lower than those reported for heavily traffic-impacted areas or tunnel environments (typically  $20$ – $80 \text{ pmol}/\text{min}/\mu\text{g}$ ), but exceed levels commonly observed in residential indoor and urban background (typically  $5$ – $15 \text{ pmol}/\text{min}/\mu\text{g}$ ).<sup>16,82,87</sup> These comparisons on OP values should be interpreted cautiously because OP measurements

are sensitive to sampling duration, particle composition, and chemicals applied in assay protocols.

### 3.3. Trend of Changes on PM<sub>2.5</sub>, BC, and Cannabinoids Concentrations, and OP Levels at Different Locations in the Cannabis Consumption Lounge

Figure 3 shows the relative changes in pollutant concentrations and OP levels across different sampling locations compared with the in-cabin location. Filter-measured PM<sub>2.5</sub> concentrations exhibited a clear decreasing trend from in-cabin to the entrance and street-front, with concentrations at the entrance and street-front corresponding to decreases of 62% and 79%, respectively (Table S7). Nevertheless, the PM<sub>2.5</sub> concentration at the retail entrance still exceeded 20  $\mu\text{g}/\text{m}^3$  (Table 3), which likely reflects a combination of ventilation design and operational factors, including frequent door opening of the smoking cabin during business hours and the lack of pressure-controlled ventilation between the smoking cabin and adjacent retail space, as well as outdoor sources. Although the smoking cabin was equipped with wall-mounted air conditioning and purification systems, contributing a high AER of 7.7  $\text{h}^{-1}$ , the absence of an exhaust or directional airflow system may have allowed particle migration into the retail area, consistent with the observed spatial gradients. Our results are consistent with previous studies showing that secondhand aerosols from the use of tobacco and electronic-cigarettes was found to infiltrate nearby units or rooms through shared ventilation systems, door gaps, and building leaks.<sup>9,88–90</sup> Bohac et al.<sup>88</sup> identified substantial particle penetration into neighboring units within multiunit housing and highlighted the presence of exposure even under voluntary or policy-guided smoking restrictions. These findings suggest that high AER alone is insufficient to mitigate secondhand particle exposure and emphasize the potential exposure risks away from smoking zone. Effective control strategies should integrate ventilation design, pressure management, and operational practices to limit particle transport beyond designated smoking areas. Engineering controls such as HEPA filtration and localized exhaust systems have been shown to effectively contain particle transport and mitigate unintended exposures.<sup>73–75</sup>

BC concentrations also decreased with increasing distance from the smoking cabin, with entrance and street-front showing reductions of 76% and 87%, respectively (Figure 3), suggesting a spatial pattern broadly consistent with PM<sub>2.5</sub>. Compared to PM<sub>2.5</sub> and BC, cannabinoids showed much larger decreases in concentrations with increasing distance from the smoking cabin. Total cannabinoids decreased sharply from the smoking cabin to the retail entrance and street-front by 98% and 99%, respectively (Figure 3). Cannabinoids are lipophilic and low-volatility compounds, which tend to bind to particles and get deposited rather than remain airborne for a long period of time.<sup>91</sup> In addition, cannabinoids degrade when exposed to light and oxygen, further limiting their potential for long-range transport.<sup>92</sup> The rapid decreases in cannabinoid concentrations, compared with the relatively moderate decreases in PM<sub>2.5</sub> and BC concentrations, are consistent with their semivolatile and reactive nature.

The overall trend of volume-normalized OP<sub>v</sub><sup>OH</sup> was consistent with that of PM<sub>2.5</sub> and BC, as OP<sub>v</sub><sup>OH</sup> at the entrance and street-front locations decreased 46% and 64%, respectively (Figure 3). Linear regression analysis suggests that concentrations of both PM<sub>2.5</sub> ( $R^2 = 0.82$ ) and BC ( $R^2 = 0.83$ ) are positively associated with OP<sub>v</sub><sup>OH</sup> (Figure S4). However, the

decreases in OP<sub>v</sub><sup>OH</sup> were much smaller in magnitude than those observed for PM<sub>2.5</sub> and BC (Figure 3), suggesting that other reactive species or environmental factors may contribute to its persistent levels away from the smoking cabin. In comparison, OP<sub>v</sub><sup>DTT</sup> exhibited a different trend (Figure 3). While OP<sub>v</sub><sup>OH</sup> consistently decreased from in-cabin to the street-front, OP<sub>v</sub><sup>DTT</sup> declined from in-cabin ( $240 \pm 150$ )  $\text{pmol}/\text{min}/\text{m}^3$  to entrance ( $160 \pm 74$   $\text{pmol}/\text{min}/\text{m}^3$ ) but then increased to  $210 (\pm 14)$   $\text{pmol}/\text{min}/\text{m}^3$  at the street-front (Table 3). The observed increases in OP<sub>v</sub><sup>DTT</sup> at the street-front reflect different redox-active chemistry and potential localized source mixtures, such as traffic-related air pollution (TRAP), which has been widely reported as a contributor to DTT reactivity in ambient environments.<sup>93</sup> TRAP is composed of a complex mixture of pollutants, including redox-active chemical compounds and transition metals.<sup>94,95</sup> Metal-rich particles have been shown to cause oxidative stress especially as measured by the DTT assay, which is highly responsive to electron-transfer reactions,<sup>82,96</sup> thereby supporting TRAP as a likely contributor to the elevated OP<sub>v</sub><sup>DTT</sup> levels at the street-front location.<sup>97</sup>

The relatively weak correlations of OP<sub>v</sub><sup>DTT</sup> with PM<sub>2.5</sub> ( $R^2 = 0.047$ ) and BC ( $R^2 = 0.022$ ) suggest that DTT reactivity at the street-front is not strongly associated with cannabis combustion-related particles, highlighting the potential contribution of noncannabis sources. This interpretation is further supported by the observation that both PM<sub>2.5</sub> and BC concentrations were lowest at the street-front, suggesting that elevated OP<sub>v</sub><sup>DTT</sup> is not driven by higher particle mass but possibly by differences in particle composition. Consistent with this interpretation, mass-normalized OP<sub>m</sub><sup>DTT</sup> was the highest at the street-front (15  $\text{pmol}/\text{min}/\mu\text{g}$ ), compared to the smoking cabin (10  $\text{pmol}/\text{min}/\mu\text{g}$ ) and the retail entrance (2.5  $\text{pmol}/\text{min}/\mu\text{g}$ ) (Table 3), indicating greater oxidative reactivity on a per-mass basis.

Our findings underscore the need for comprehensive chemical characterization on PM<sub>2.5</sub> constituents to better understand potential contributors to OP in cannabis-related environments.<sup>56</sup> The distinct responses of OH and DTT assays show that OP cannot be attributed to a single source or chemical species based on the present measurements. It should be noted that the reported OP in this study does not allow for source-specific contribution. Therefore, the OP results should be interpreted as indicators of overall particle oxidative activity rather than source-specific toxicity or direct health outcome. Future studies incorporating targeted measurements of redox-active compounds, exposure modeling, and health effects analyses are needed to establish source-toxicity relationships, which helps translate OP metrics into direct indicators of health risks.

This study has several limitations. First, measurements were conducted at a single cannabis consumption lounge, which limits the generalizability of our findings to other lounges or similar settings with different size, ventilation design, occupancy patterns, and consumption behaviors. Due to restrictions on sampling locations and access time, we were unable to collect data in offices or at vending counters, which may also represent important employee work areas. In addition, the metal data set was based on one integrated sample per selected cannabis business, while BC, cannabinoids, and OP were measured from three week-long integrated samples in the cannabis consumption lounge. Therefore, these measurements should be interpreted as exploratory and descriptive field observations rather than as evidence for robust ANOVA- or regression-based inference. Sampling at the

three locations was also not concurrent, the short-term PurpleAir measurements carry measurement uncertainty, and no airflow or pressure-differential data were collected; therefore, the observed spatial gradients are consistent with possible pollutant migration but cannot establish directional transport from the smoking cabin. Second, week-long integrated filter samplings may not capture short-term exposure spikes observed in the PM<sub>2.5</sub> time-series, particularly for cannabinoids and OP, which may vary during active cannabis use. Therefore, the maximum or acute exposures on cannabis chemicals and OP, as well as the potential health risks may be underestimated when relying solely on longer-term averages. Further, as CBN is a secondary oxidation product from partial oxidation of THC, its measured concentration may be elevated during long sampling durations. Therefore, the sum of THC and CBN is calculated as an approximate indicator for estimating total cannabinoids. Lastly, while acellular OP assays provide useful information on chemical oxidative activity, they do not directly assess biological responses or health outcomes. As a result, these results should be interpreted as indicators of particle redox activity rather than direct evidence of health effects. In addition, because the PTFE filters were analyzed by optical transmissometry for BC before the OP assays, the potential influence of these prior optical measurements on the OP responses could not be directly evaluated in this study. Future research focusing on the health effects of cannabis exposure is needed to link the observed OP levels to health implications. In-vivo experiments or epidemiological models should be considered to investigate the toxicological impacts of cannabis aerosols on respiratory and cardiovascular health. Longitudinal exposure studies among employees are also warranted to assess chronic occupational risks. Nevertheless, this study provides comprehensive analysis of the chemical composition and OP in cannabis business environments with active indoor cannabis smoking. Elevated concentrations of metals, BC, and cannabinoids highlight the complexity of secondhand cannabis aerosols and their potential health implications. Together, these findings call for improved control strategies and health assessments to protect public and occupational health in emerging cannabis businesses.

## ■ ASSOCIATED CONTENT

### SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsestair.6c00144>.

Additional experimental methods for BC quantification, OH and DTT assays, QA/QC procedures, AUC calculation, and emission rate estimation; supplementary tables of metal concentrations from previous related studies, PM<sub>2.5</sub> measurements between PurpleAir and UPAS gravimetric methods, OP analyses, and spatial variations on pollutant concentrations; and supplementary figures showing correlations in BC and PM<sub>2.5</sub> concentrations, PM<sub>2.5</sub> time series at three cannabis businesses, OP comparisons across three sampling locations in the cannabis consumption lounge, and linear regression analyses between pollutant variables (PDF)

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### Notes

The authors declare no competing financial interest.

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