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Original Article

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Occupational Exposure to Particulate Matter and Volatile Organic Compounds in Two Indoor Cannabis Production Facilities

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Abstract

Legal commercial cultivation and processing of cannabis is a rapidly growing industry in multiple countries. However, to date little effort has been made to characterize and identify the various occupational hazards that workers may be facing in the cannabis production industry, including airborne contaminants that may affect the human respiratory system. In the current study, we quantified occupational exposures to particulate matter (PM) and volatile organic compounds (VOCs) in various task zones of two indoor cannabis facilities in Washington State. Full-shift (8-h) area measurements of PM and VOCs were collected in each task zone. Measurement devices were placed near the employee's work area in order to attempt to estimate the personal exposure to the contaminants. In each task zone we measured particle number concentration, particle mass concentration (PMC), cumulative size distribution of the particles, and total terpene mass concentrations. The mean PMCs were greater in task zones that required the employees to manipulate the cannabis plants and materials. The arithmetic mean PMC for the trim task was 60 μg m^{-3}, preroll task was 45 μg m^{-3}, grow task was 42 μg m^{-3}, and the referent office area was 27 μg m^{-3}. When comparing each task zone PMC to the office referent PMC, the trim task, and the preroll task were significantly higher than the referent group (*P*-values both <0.05). The arithmetic mean terpene mass concentration for the trim task was 36 mg m^{-3}, preroll task was 9.9 mg m^{-3}, grow task was 15 mg m^{-3}, and for the office referent space was 4.9 mg m^{-3}. Compared with the office space, only the trim task area had significantly elevated terpene mass concentrations (*P*-value <0.01). We observed a weak but statistically significant correlation between PMC and total terpene mass concentrations (rho = 0.42, $P < 0.02$). Overall, we observed that exposures to respiratory hazards were highest in task zones where cannabis plants and material were manipulated by workers, including the trim, preroll, and the grow task areas. These observations can help inform the employer of the task zones where exposure to respiratory hazards are the highest, and where it may be beneficial to deploy control measures to reduce worker exposures.

Keywords: allergy; horticulture; indoor air; marijuana; respiratory disease

Introduction

Laws relating to production, possession, and use of cannabis have recently become more permissive in a number of countries (Mead, 2019; Hall and Lynskey, 2020). In the USA, federal law prohibits the use, possession, sale, cultivation, and transportation of cannabis and notes of its high abuse potential (Hasin, 2018). However, there are currently 33 states and 4 permanently inhabited US territories, and the District of Columbia that have passed initiatives to legalize the medical and/or recreational use of cannabis, including Washington State (NCSL, 2018). The increased use of cannabis in recent years has seen the legal cannabis industry grow to a billion-dollar-a-year industry responsible for supporting approximately 125 000–160 000 workers in the USA in 2018 (Hasin, 2018; McVey, 2018). McVey *et al.* report that growth of this industry is expected to support as many as 340 000 full-time jobs in the next 5 years, just over doubling the current industry levels (McVey, 2018). As the industry continues to welcome more workers into the job force, it is necessary to further examine the potential occupational health exposures that may be present.

The process for producing cannabis in an indoor facility begins in a clone room. Cuttings from mature donor plants are removed to create new seedlings/clones (Couch *et al.*, 2018). In the grow rooms, the life cycle of the plants is controlled by the light/dark conditions created by the grow lights and is determined and manipulated by the producer in order to push the plants from the vegetative into the flowering stage. Indoor growing operations can typically achieve three to four flowering cycles per year, while outdoor production is limited to a single grow cycle due to seasonality and weather patterns. Once mature, workers harvest the plants by removing large stems and hanging the plants to dry (Couch *et al.*, 2018). The plants are then destemmed by hand and the cannabis flower is sorted and rated based on a combination of visual, olfactory, and potency factors. The highest quality flower is hand trimmed to remove leaves and remaining stems and packaged as full, intact flower. The lower quality flower is mechanically trimmed and crushed to create a coarse powder that will be transferred to be rolled into joints, or extracted using solvents to create concentrates that are high in tetrahydrocannabinol and other cannabinoid content.

Currently, there are a very limited number of studies that have examined occupational exposures in cannabis production and processing facilities. A best practices guide recently released by the Colorado Department of Public Health and Environment identified a range of potential biologic, chemical, and physical occupational health hazards for cannabis workers (State of Colorado, 2017). Of the studies available, many focus on the potential for significant physical and ergonomic hazards, however respiratory hazards including exposures to pesticides, molds, endotoxins, volatile organic compounds (VOCs), and particulate matter (PM) were all noted as potential exposures of concern. There remains a lack of task-specific, full-shift quantitative data regarding worker exposure to these hazards in the cannabis industry.

Due to the lack of prior studies of PM exposure in the cannabis industry, we must draw connections between the work that is done in agricultural settings involving production and processing of biologically similar species such as hemp and hops. Airborne organic dusts in hemp production can be composed of a variety of respiratory irritants and have been associated with respiratory infections, irritation, inflammation, and allergic responses (Davidson *et al.*, 2018). Additionally, a series of studies conducted in the hemp production industry indicated high prevalence of byssinosis, reduction of respiratory and pulmonary function, and chronic symptoms such as cough, phlegm, shortness of breath, and chest tightness among the workers (Bouhuys *et al.*, 1967; Fishwick *et al.*, 2001; Davidson *et al.*, 2018).

A study by Martyny *et al.* in 2013 briefly discussed the presence of VOCs that are associated with the distinct smell of cannabis in illegal indoor grow operations. That study reported higher VOC levels in the grow rooms versus the other areas of production and processing (Martyny *et al.*, 2013). In terms of VOC exposures, it is believed that the terpenes, a specific class of VOC that are emitted when working with the cannabis plants, could potentially contribute to the respiratory and dermatological symptoms among workers (Fent *et al.*, 2011). Terpenes are compounds that are produced by plants and are responsible for the distinct scent and taste of cannabis (Fent *et al.*, 2011; Couch *et al.*, 2018). While low levels of terpenes are unlikely to cause adverse health effects, these compounds have the ability to react with oxidants found in indoor environments and form highly oxidized species which are suspected to cause respiratory tract irritation and airflow limitation (Couch *et al.*, 2018). A NIOSH Health Hazard Evaluation described several monoterpenes that were detected in a

cannabis manufacturing facility, however no quantitative terpene or task-specific data were reported (Couch *et al.*, 2018). Studies that indicated respiratory health effects among workers exposed to terpenes varied among workplace but largely included alpha-pinene, beta-pinene, beta-myrcene, beta-caryophyllene, and limonene (Eriksson *et al.*, 1997; Fent *et al.*, 2011).

The primary objective of this study was to measure concentrations of PM and VOCs (terpenes) in specific task zones of two indoor cannabis cultivation and processing workplaces.

Methods

Study design and research setting

This study is a pilot observational study that examined occupational exposures to airborne contaminants for workers who grow and process cannabis. The study utilized area sampling with both continuous reading and integrated sampling methods to measure PM and VOCs in two facilities. Observations of employees' work activities were recorded on each day of sampling.

All data that were collected for this research study were gathered from two cannabis production facilities located in Washington State. The primary facility is a Tier 3 cannabis grower and processor that uses conventional cultivation methods and is permitted to grow up to 30 000 square feet of plant canopy—the largest size allowable in Washington State. In addition to growing their own product, the primary facility seasonally purchases outdoor-grown cannabis from other growers, which they then process into consumer products. This facility employs approximately 45 workers. The secondary facility in which data were collected is a smaller Tier 2 cannabis grower with a total of approximately 20 employees. Their production facility is an indoor factory in a converted warehouse, and their license permits them to grow up to 10 000 square feet of plant canopy. They farm using organic (pesticide free) methods. The work organization at the secondary facility is more siloed than at the primary facility, with individual workers assigned exclusively to cultivation or processing of dry goods (i.e. workers do not rotate among different tasks).

Data collection and field work

Data collection occurred in four separate campaigns that occurred in October and December of 2018, and January and June of 2019. At the primary facility sampling was conducted on the Monday and Friday of the representative week, for a total of 8 days of sampling. Only a single sampling visit was made to the secondary facility. All samples were collected during a typical day shift from 8:00 am until 4:30 pm. The placement of samplers throughout the facility corresponded to unique task zones, where employees were present for the majority of the work day, and where high exposures were assumed to occur due to constant handling and manipulation of plants and plant material. The four unique task zones of interest included the trimming, prerolling, growing, and office areas.

PM sampling

Continuous particle number concentrations (PNCs) in each of the four distinct task zones were measured using the Dylos DC1100 Pro (Dylos) optical particle counter. The Dylos samplers measure PNCs in four size bins of varying aerodynamic diameters. Bin 1 (b_1) measured particles with an aerodynamic diameter greater than 0.5 µm, Bin 2 (b_2) measured particles greater than 1.0 µm, Bin 3 (b_3) captured particles greater than 2.5 µm in diameter, and finally Bin 4 (b_4) captured particles greater than 10 µm in diameter. The Dylos devices logged PNCs in each of these four bins once every second, and integrated these into 1 min PNC averages over the sample duration. Previous studies by Jones *et al.*, and Manikonda *et al.* indicated that these Dylos devices demonstrate good accuracy and precision when compared with referent devices (Jones *et al.*, 2016; Manikonda *et al.*, 2016).

Four Dylos monitors were utilized on each unique sampling day, one monitor per each task zone. The monitor was positioned as close to the breathing height and the work zone of the employees as possible in each of the four task zones (trim, preroll, grow, and office). The inlets of each of the samplers faced toward the work area.

VOC and terpene sampling

Integrated area air sampling for terpenes followed the NIOSH Manual of Analytic Methods (NMAM) 1552: Terpenes (Terpenes: Method 1552, 1996) with some modifications. The pump and sorbent tubes for terpene air sampling were collocated with the Dylos PM monitors. The samples were collected on sorbent tubes packed with anasorb CSC (SKC Inc., P/N 226-09). SKC AirChek and PXCR personal sampling pumps (SKC Inc., Eighty-Four, PA, USA) were utilized to maintain a flow rate through the charcoal sorbent tube of approximately 200 ml min^{-1}. Pre- and postcalibration of the flow rate through the sorbent tubes was determined using a DryCal Defender primary gas flow calibrator (SKC Inc., Eighty-Four, PA, USA). Following sample collection, the sorbent tubes were securely capped and wrapped

in aluminum foil and stored at –20°C until extraction occurred.

Total VOCs in each task zone within facility #1 were also monitored using a custom-built continuous reading monitor with photoionization detector (PID) sensor. With this device, a PID sensor (piD-Tech eVX, item # 045-013, Ametek Mocon, Lyons, CO, USA) is connected to an Arduino microcontroller and an SD card installed for data logging. The value that is logged on the SD card every 5 s is an arbitrary signal intensity in analog-to-digital (ADC) units that represents the level of VOCs in that specific task zone. The PID was calibrated using isobutylene in order to convert the signal intensity into VOC concentration (mg m^{-3} isobutylene equivalents). The single VOC PID sensor was placed in a single task area for the duration of a full shift of sampling and then rotated through the remaining three task zones on subsequent sampling days. Due to data logging errors, only 5 days worth of measurements were recovered from this device.

Sample and data analysis

PM data

Following each day of sampling, the particle data were downloaded from the Dylos instruments using PuTTy software (beta 0.67) and imported into the RStudio statistical program (RStudio 0.99.903 using R 3.3.1; Boston, MA, USA). In order to get PNCs for each separate bin, four particle bins sizes (µm) ($0.5 \leq b_1 \leq 1.0$, $1.0 \leq b_2 \leq 2.5$, $2.5 \leq b_3 \leq 10.0$, and $10.0 \geq b_4$) were created. PNC values from each bin were then converted to particle mass concentrations (PMCs) using equation (1) and assuming a consistent aerosol density of 1.5 g ml^{-1}. The aerosol density value was chosen based on a literature review of PM monitoring in various agricultural settings where similar processing and plant matter were being manipulated and aerosolized (Parnell *et al.*, 1986; Lee *et al.*, 2006; Cambra-Lopez, 2011). The midpoint of each bin on the log scale was used due to the expectation that the particle count data would be log normally distributed, except for fourth bin where, by convention, the lower cut size of 10 µm was used (d_1 = 0.71 µm, d_2 = 1.58 µm, d_3 = 5.00 µm, and d_4 = 10.00 µm) (Blanco *et al.*, 2019). To get total PMC for each task zone and each sampling day, all four bin's PMCs were aggregated.

Equation 1: Conversion from PNC to PMC. d_b = midpoint of each size bin on the log scale in µm; ρ = particle density (assumed to be 1.5 g ml^{-1})

$$\mathrm{PMC_{Total}} = \sum_{b=1}^{4} \left(\mathrm{PNC}_b \times \frac{\pi}{6} \times d_b^3 \times \rho \right)$$

$$\mathrm{PMC_{Total}} = \sum_{b=1}^{4} \left(\left(\frac{\mathrm{count}}{0.01\ \mathrm{ft}^3} \times 100 \times \frac{35.3147\ \mathrm{ft}^3}{\mathrm{m}^3} \mathrm{PNC}_b \right) \times \left(\frac{\pi}{6} \right) \times \left(\frac{\text{bin diameter } (\mu\mathrm{m})}{10^6\ \mu\mathrm{m/m}} \right)^3 \times \left(\text{assumed density } \left(\frac{\mathrm{g}}{\mathrm{cm}^3} \right) \times \frac{10^6\ \mu\mathrm{g}}{\mathrm{g}} \times \frac{10^6\ \mathrm{cm}^3}{\mathrm{m}^3} \right) \right)$$

Terpene data

The analysis of 21 specific terpenes was performed by using gas chromatography–mass spectrometry (GC/MS) utilizing an Agilent Technologies 7890A GC and 5977A MSD (Agilent Technologies, Santa Clara, CA, USA), scanning from *m/z* 30 to 250. Terpene concentrations were determined by analyzing a set of six calibrants over the range of 25–1000 ng ml^{-1}. Calibration curves were calculated by linear regression ($r^2 > 0.99$) and applied to calculate analyte concentrations in environmental samples using Agilent Technologies MassHunter Quantitative Analysis software. Table 1 lists each of the individual 21 terpenes that were analyzed by GC/MS and the corresponding quality control data averaged from the December, January, and June sampling campaigns including average spike recovery percentage, recovery relative standard deviation, and limit of detection values.

In order to calculate mass concentrations of total terpenes from each sample, the batch recovery percentage from the analysis was applied to the uncorrected mass for each individual terpene to get a total corrected mass in nanograms (ng). Terpene masses were divided by sample air volumes to obtain air concentration in milligrams per cubic meter for each of the 21 individual terpenes. Finally, each terpene-specific mass concentration was summed for each sample to get total terpene mass concentration (mg m^{-3}).

Statistical analysis

All statistical analysis was undertaken using R (RStudio 0.99.903 using R 3.3.1; Boston, MA, USA).

The first objective of this study was to assess the differences in PNC, PMC, and size distributions among the four specific task zones within the primary and secondary research facilities. Data were assessed for normality using the Shapiro–Wilk test, and histograms of raw and log-transformed data were examined to visualize data distributions. Frequency distribution plots of the PMCs and terpene mass concentrations indicated

Table 1. List of 21 terpenes analyzed via GC/MS from sorbent tube sampling and associated quality assurance data.

Terpene	Average recovery (%)	Recovery RSD (%)	Limit of detection (ng)
Alpha-pinene	80	10	25
Camphene	81	10	25
Sabinene	74	10	25
Beta-pinene	79	10	25
Beta-myrcene	62	12	50
p-Mentha-1,5-diene	55	9	25
1(s)-(+)-3-carene	63	9	25
Alpha-terpinene	62	9	25
R(+) limonene	71	19	25
Ocimene Peak 1	63	11	100
Eucalyptol	76	14	50
Ocimene Peak 2	46	22	50
Gamma-terpinene	58	7	50
Terpinolene	44	27	100
(+) and L(−) fenchone	76	31	100
Isoborneol	99	7	250
Trans-caryophyllene	54	36	100
Alpha-cedrene	52	28	100
Alpha-humulene	63	11	100
Valencene	39	17	100
(+) cedrol	44	14	250

RSD, relative standard deviation.

that terpene mass concentrations exhibited an approximate log normal distribution, but PMCs did not conform to either a normal or a log normal distribution. Summary statistics for PNC and PMC among each task zone were calculated, and intertask zone variation of PMC and PNC was examined using the Mann–Whitney *U* test. For this study, it was of interest to compare the trim, preroll, and grow task zones each to the reference location of the office. Additionally, particle size distributions using mass fraction data from the Dylos monitors were summarized using the mass median aerodynamic diameter (MMAD) and the geometric standard deviation (GSD).

The secondary objective of this study was to assess the differences in total terpene mass concentrations among the four task zones. Descriptive statistics were calculated and the Mann–Whitney *U* test was used to examine the intertask variation of mean terpene mass concentrations of each task zone compared with the office referent area. As a secondary analysis, summary statistics for the continuous VOC PID sensor data were calculated.

Spearman rank-order correlation was used to assess the association between total PMC and total terpene mass concentrations of each individual task zones.

Results

Particulate matter

PNCs and PMCs were quantified and compared across the four individual task zones in the two indoor cannabis production facilities. Summary statistics for PNC and PMC, reported separately for each facility, can be found in Table 2. PNC and PMC values on the one sampling day at facility #2 were within the range of the values measured over 8 days of sampling at facility #1. Therefore in Figs 1 and 2 and in the discussion below, data from both facilities are aggregated by task zone.

The greatest arithmetic mean PNC levels were measured in the trim task zone, followed by preroll, office, and grow task zones. The arithmetic mean PNCs were 4.2×10^6, 3.9×10^6, 2.7×10^6, and 1.4×10^6 count m^{-3} for the trim, preroll, office, and grow task zones, respectively. Boxplots in Fig. 1 demonstrate the within- and between-task zone variability in PNC concentrations.

Similarly, arithmetic mean PM concentrations were highest in the trim task area (60 µg m^{-3}), followed by the preroll task area (45 µg m^{-3}), the grow task area (42 µg m^{-3}), and finally the lowest arithmetic mean PM concentrations were detected in the referent office task area

Table 2. Summary statistics for PNC and PMC.

Location	Facility #1 (8 sample days)				Facility #2 (1 sample day)
	Mean	Median	St. Dev.	Interquartile range (IQR)	
PNC (count m^{-3})					
Trim	4.4×10^6	3.9×10^6	1.9×10^6	3.3×10^6–4.8×10^6	2.0×10^6
Preroll	4.3×10^6	4.2×10^6	1.4×10^6	3.4×10^6–5.5×10^6	0.5×10^6
Grow	1.4×10^6	1.1×10^6	1.4×10^6	2.3×10^6–2.4×10^6	1.8×10^6
Office	2.7×10^6	2.2×10^6	1.4×10^6	1.8×10^6–3.7×10^6	2.7×10^6
PMC (μg m^{-3})					
Trim	59	50	25	44–78	8
Preroll	50	46	21	33–59	10
Grow	43	46	79	0.5–35	44
Office	19	17	6.3	14–21	99

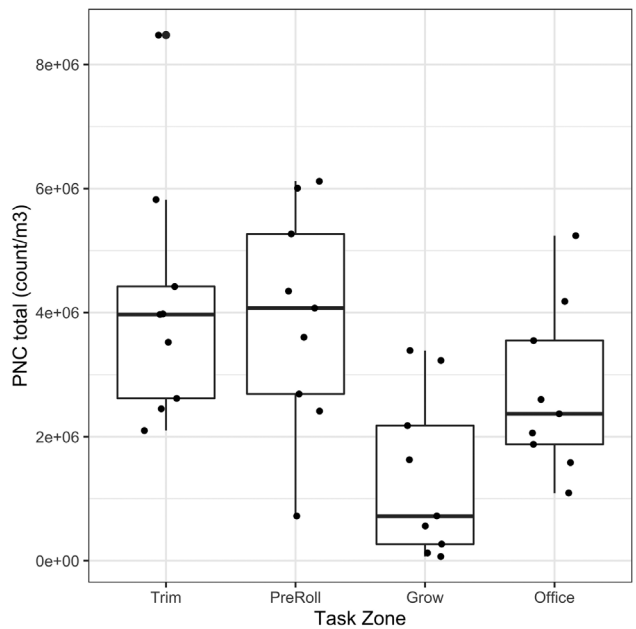

Figure 1. Boxplot of mean PNCs of the aggregate daily data for each sampling day across the four task zones.

(27 μg m^{-3}). Within- and between-task zone variability in PM concentrations are plotted in Fig. 2.

PNC concentrations in the preroll task area were significantly higher compared with the office referent group (P-value = 0.05). In contrast, PNC concentrations in the trim task area (P-value = 0.08) and the grow area (P-value = 0.09) were not significantly different compared with the office task area.

Similarly, PM concentrations in the trim task area (P-value < 0.01) and the preroll task area (P-value = 0.05) were significantly different compared with the referent office area. The difference in PMC between the grow task area and the office was not significantly different (P-value = 0.44).

Differences in particle size distributions were assessed across task zones within the facility. Following sample collection and analysis, particle size data were represented using a cumulative probability distribution, defined as the fraction of all particles with a diameter less than the cut point of interest determined by the sampling equipment specifications (Ramachandran, 2005). Fig. 3 illustrates particle size distributions for each task zone based on the four size bins of the Dylos DC1100 Pro monitors. The MMAD and the GSD are given in

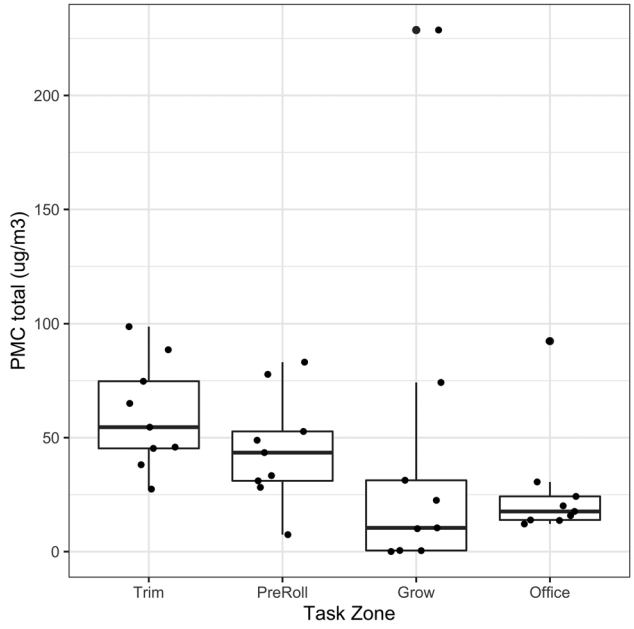

Figure 2. Boxplot of mean PMCs of the aggregate daily data for each sampling day across the four task zones.

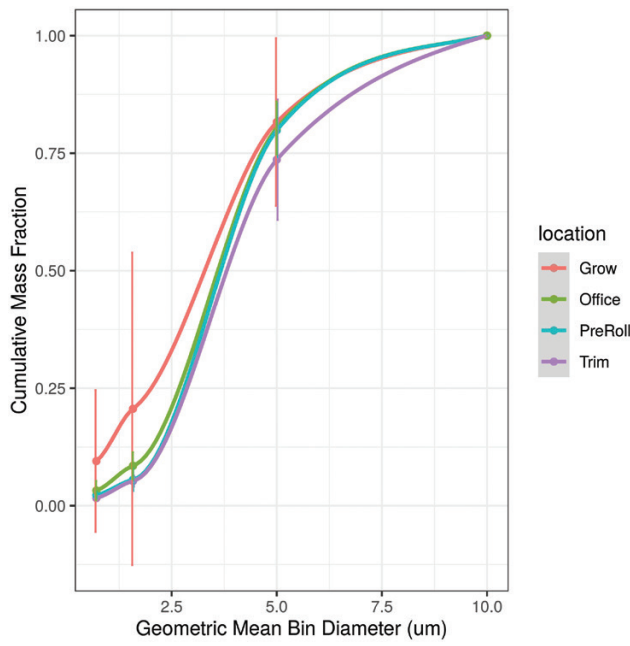

Figure 3. Cumulative distribution of particle mass fraction data based on bin diameter cut points. Data for each task zone from each individual sampling day were aggregated to obtain a mean PNC for each size bin. Bin averages were then converted to PMC, and finally the PMC values for each bin for each sampling day were averaged across days within task zone, and those averages plotted to create the distribution lines. The vertical lines represent standard errors from the task area samples ($n = 9$ per task area).

Table 3. Particle size distributions were similar across all for task zones. Aggregated across both facilities, the task area with the highest MMAD was the trim area with a value of 3.76 µm. The preroll and the office task areas had similar MMAD at 3.55 µm, while the grow rooms had the smallest MMAD value of 3.16 µm.

Volatile organic compounds

The primary variables of interest were total terpene mass concentrations (mg m^{-3}) and total VOC concentrations (mg m^{-3}) among the four unique task zones of interest. Data from the full-shift sorbent tube samples were used to calculate summary statistics for total terpene mass concentrations (Table 4) and to plot inter- and intralocation variability (Fig. 4). The boxplot demonstrates that the trim task area has the highest terpene concentrations (36 mg m^{-3}) and the greatest amount of intralocation variability. The other task zones resulted in arithmetic mean terpene concentrations of 9.9 mg m^{-3} in the preroll area, 15 mg m^{-3} in the grow area, and finally 4.9 mg m^{-3} in the referent office area. Total terpene concentrations in the trim area are significantly higher compared with the referent office

Table 3. Summary statistics for MMAD and GSD among task zones.

Location	Facility #1 (8 sample days)		Facility #2 (1 sample day)	
	MMAD (µm)	GSD (µm)	MMAD (µm)	GSD (µm)
Trim	3.8	1.6	3.7	1.8
Preroll	3.6	1.6	2.9	1.5
Grow	3.2	1.8	3.5	1.6
Office	3.6	1.7	3.8	1.8

Table 4. Overall total terpene mass concentration by task area from sorbent tube sampling (mg m^{-3}).

Location	Facility #1 (8 sample days)				Facility #2 (1 sample day)
	Mean	Median	St. Dev.	IQR	
Trim	34	16	44	9.4–36	45
Preroll	11	5.6	11	4.0–13	6.2
Grow	16	6.9	20	1.8–20	19
Office	1.5	1.5	0.85	1.1–2.2	28

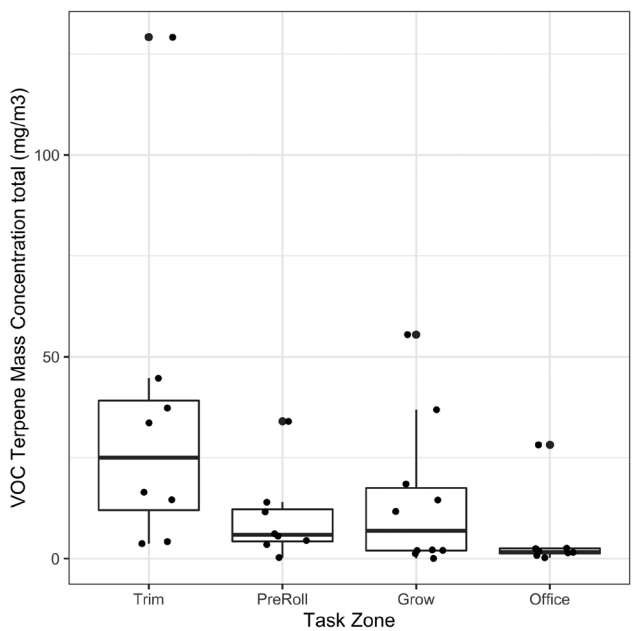

Figure 4. Boxplot of VOC total terpene mass concentration by task area (mg m^{-3}).

concentrations (*P*-value < 0.01). However, there is no statistically significant difference in total terpene mass concentrations in the preroll (*P*-value = 0.06) or grow task areas (*P*-value = 0.23) when compared with the referent office space task area.

Total VOC concentrations among task zones within the facility were measured using the VOC PID sensor. Total VOC concentrations were greatest in the trim task area task area (7.1 mg m^{-3} isobutylene equivalents), and lower in the preroll, grow, and office areas (5.5, 3.0, and 1.5 mg m^{-3}, respectively). In addition to sampling in the usual task areas, a single day of data was collected using the VOC PID sensor in the drying room during a plant harvest. The dry room task area reached the saturation point on the PID sensor of 53 mg m^{-3} isobutylene equivalents within the first hour of sampling and remained at that concentration for the remainder of the 6-h sampling period.

Correlation between PMC and total terpene mass concentration

A visual inspection of the data was conducted to determine if the relationship between PMC and total terpene mass concentration is linear. A plot of the relationship for the combined data from the four task zones is shown in Fig. 5. The correlation coefficient indicated a weak but statistically significant, positive relationship between the two variables (rho = 0.42, *P*-value = 0.02). When broken down into individual task zones, the associations between PMC and terpene mass were weak and not statistically significant in all cases: trim task zone (rho = 0.31, *P*-value = 0.46), preroll and the office task areas (rho = 0.24, *P*-value = 0.58 for both areas), and grow task area (rho = –0.22, *P*-value = 0.58).

Discussion

Particulate matter

Overall, PNCs were greatest in task areas where constant manipulation and handling of the cannabis plants and plant materials occurred. The two task areas where PNC and PM concentrations were greatest were the trim task area and the preroll task area. The high PNC in the trim task zone is likely a result of the mechanical grinding of the cannabis flower into coarse powder, hand screening of cannabis flower through size selective filters to separate small stems and seeds, or the mechanized filling of joint cones via the 'knock-box' device. These tasks occurred periodically throughout the entirety of the work shift and were associated with elevations in dust levels, observable in the time series data from the Dylos monitors. It was noted that during daily observations of worker activities in these task zones that several of the workbench spaces had visible accumulation of organic plant material. In task areas where worker activities that involved manipulating the cannabis plants and materials

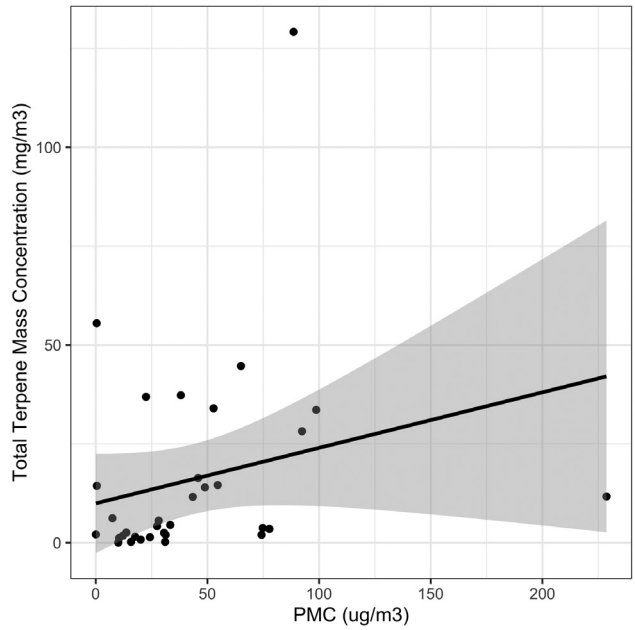

Figure 5. Scatterplot of PMC versus VOC total terpene mass concentration across all task areas.

were more intermittent, such as the grow task zone, the PNC exposure values were much lower. Although workers in the office task area, which served as the referent group in this study, seldom handled unpackaged cannabis plant material, the mean PNC concentration was greater than that of the grow task area. One possible explanation for this finding might be removal of ultrafine particles by deposition on the vegetation in the grow rooms. Several studies have reported that vegetation can be effective at removing ultrafine particles in indoor and outdoor settings (Stapleton and Ruiz-Rudolph, 2018; Wang *et al.*, 2019). In the 1 day of sampling undertaken at facility 2, PNC and PMC concentrations in the office area were higher than in any other task zone in this facility. Potential particle sources in the office area that were not present in the other areas of the facility include an office printer/copier, resuspended dust from carpeted floor and couch, and, compared with other task zones, greater foot traffic. In addition, at both facilities the air-handling system in the office area lacked some of the air-filtration devices present in the air-handling system in the other task zones. Both cannabis production facilities are located in industrial areas near to roadways with substantial truck traffic, where ambient PM and PMC may be elevated. For comparison, typical ambient PNC levels in an industrial area near Birmingham, England ranged from 1.0×10^4 to 6.0×10^7 particles m^{-3} when sampling for PM in the size ranges of 0.5–10.0 µm (Taiwo *et al.*, 2014). In addition, typical PNC measurements in a grain handling and harvesting facility ranged from 1.2×10^6 to 5.8×10^7 particles m^{-3} when sampling for PNC in the size ranges of 0.7–10.0 µm (Cho *et al.*, 2010). The range of PNCs that we observed in our study is similar to those reported in the two studies cited above.

Overall, aggregate arithmetic mean PM concentrations from the sampling campaigns ranged from 60 µg m^{-3} in the trim task area to 27 µg m^{-3} in the referent office area. As with the PNCs, average PMC levels were highest in the trim and preroll areas where cannabis plants and plant materials were manipulated by workers, and were lowest in the grow and office task areas. Few studies in the literature have reported measures of personal exposures to organic dusts from cannabis or hemp processing activities. PM concentrations for 8-h full-shift sampling in this research study were below those reported by Fishwick *et al.*, Zuskin *et al.*, and Couch *et al.* Fishwick *et al.* found that when sampling in the inhalable fraction for workers processing hemp, personal organic dust exposures ranged from 10.4 to 79.8 mg m^{-3}, however the length of sampling was not recorded and the study did not note whether or not the personal samples were task- or location-specific measurements (Fishwick *et al.*, 2001). Zuskin *et al.* reported high personal exposure levels during production activities when sampling for an 8-h work shift in the respirable range (1.3–38.4 mg m^{-3}) in a hemp production facility (Zuskin *et al.*, 1990). Again, this study did not address whether personal respirable PM samples on workers were from generalized work activities, or if they occurred during a single task or in a single location within the facility. Couch *et al.* reported worker area sampling results that ranged from 0.01 to 20.5 mg m^{-3} during a typical 45-min grinding operation at a cannabis production facility (Couch *et al.*, 2018).

None of the samples collected in this study resulted in a PM concentration that exceeded the US OSHA 8-h Time-Weighted Average (TWA) Permissible Exposure Limit (PEL) for Particulates Not Otherwise Regulated (Total) of 15 mg m^{-3} or the ACGIH TWA Threshold Limit Value of 10 mg m^{-3}. Based on this standard, the facilities in which this study took place are compliant with occupational regulations pertaining to exposures to PM. However, due to the fact that workers in these facilities have reported experiencing respiratory health effects at the lower PM concentrations that were sampled during this research study (Ghodsian, 2019), it indicates that exposure to particles at levels below the OSHA PEL may cause respiratory irritation or other serious health effects. Bouhuys *et al.* and Zuskin *et al.* reported a high prevalence of byssinosis (77% and a range of 47–67%, respectively) in hemp workers, and acute respiratory symptoms such as decreased FEV_1, chest tightness, cough, and dyspnea in healthy adults after just an hour of exposure to hemp dust (Bouhuys *et al.*, 1967; Zuskin *et al.*, 1990). Currently, there is no standard in place that regulates occupational exposure specifically to organic dusts from cannabis plants and related materials. Based on the evidence reported from this study and from the few studies published in literature regarding occupational exposures to cannabis, we recommend that a health-based exposure standard specifically for cannabis dusts is developed. In the interim, the ACGIH TLV standard for cotton dust [0.1 mg m^{-3} (8-h TWA)] could be implemented as an interim occupational exposure standard for these facilities until a cannabis standard is developed and adopted. However, a cannabis-specific standard may need to be even lower since it has been suggested that components of cannabis may have an even greater proinflammatory potential as compared with cotton dust (Zuskin *et al*, 1976; Davidson *et al.*, 2018).

Results from the particle size distribution analysis were consistent with aerosol distributions of typical

occupational settings. Ramachandran *et al.* describe occupational aerosols to be log normal distributed with GSDs ranging from 1.5 to 3.5 (Ramachandran, 2005). Examples of MMADs in agricultural workplace settings include air samples collected from inside dairy barns with MMAD (GSD) of 13.5 µm (2.1), and samples collected from a grain facility with MMADs (GSDs) for corn grain dust of 13.2 µm (1.8) and wheat dust of 13.4 µm (2.1) (Kullman *et al.*, 1998; Boac *et al.*, 2009). In the case of this research study, MMADs ranged from 3.16 to 3.76 µm and GSDs ranged from 1.62 to 1.77, which indicates that particles in the cannabis facility were on average smaller than those observed in the agricultural workplaces cited above.

Volatile organic compounds

Overall, aggregate arithmetic mean total terpene mass concentration exposures from the sampling campaigns ranged from 36 mg m^{-3} in the trim task area to 4.9 mg m^{-3} in the referent office area. Since it is the terpene compounds that are responsible for the unique scent of the cannabis plant it was hypothesized that task zones that required a great deal of plant manipulation and thus a release of the aroma, such as grinding or trimming, would result in the highest levels of total terpene exposures. This was found to be true in the case of the trim task area, but the grow task area resulted in the second highest value of aggregate mean total terpene mass concentration. Comparison of total terpene mass concentration averages in each task zone to the average of the office referent task zone resulted in only the trim task zone having statistically significant differences in average total terpene mass concentration levels compared with the office (P-value < 0.01).

Eriksson *et al.* described occupational illness in sawmill workers that was related to terpene exposures (Eriksson *et al.*, 1997). Newmark described a case study of a brewery worker with respiratory and dermal allergy in association with exposure to Hops (Newmark, 1978), which contain a similar suite of terpenes to cannabis. The patient also had a positive skin reaction to beta-myrcene. Additionally, terpenes present unique physiochemical properties that allow them to be readily absorbed through the skin and gastrointestinal tract (Davidson *et al.*, 2018). This indicates a potential for health concerns associated with occupational exposure to terpenes. Currently, there are very few occupational standards regarding terpene exposures. The American Industrial Hygiene Association (AIHA) has set an 8-h Workplace Environmental Exposure Levels Guideline for limonene at 30 ppm as an 8-h TWA (AIHA, 2010). The European Union (EU) has established 8-h TWA exposure standards for terpenes range from 20 to 100 ppm (which corresponds to approximately 46–229 mg m^{-3} isobutylene equivalents) (Davidson *et al.*, 2018). Our measurements were typically below 50 mg m^{-3}, however there were four samples greater than 50 mg m^{-3}, and two samples greater than 100 mg m^{-3}. Although this research study does not differentiate whether adverse health effects reported by cannabis workers are a result from exposure to PM or terpenes, since the US lacks a standard at the state or federal level for exposure to terpenes in occupational settings, an EU standard might be considered for adoption.

Limitations

There are several limitations in this study that are notable and could have been addressed with more time and resources. One important limitation of this study is the reliance on area concentration measurements, rather than personal exposure measurements, to characterize and quantify airborne contaminant concentrations across task zones within the facilities. The area samples may not be fully representative of breathing zone exposures of workers that may have been moving between different microenvironments during a typical work day. Ideally, measurements of airborne contaminants would have been done at the individual level rather than the task level. Having a more extensive set of air samples would also have made the data set more robust.

Secondly, the data presented are for a limited number of samples from only two indoor cannabis production facilities. Future studies should include sampling at multiple cannabis producers and processors and at varying scales of production including indoor, greenhouse, and outdoor production facilities to more fully characterize the varying occupational exposure levels across the cannabis industry.

A final limitation of our study is the absence of chemical characterization of the airborne particles measured in these facilities. Prior work has suggested that either cannabis-specific antigens, or microbial contaminants could be associated with respiratory symptoms in individuals exposed to cannabis.

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Conflict of interest

The authors declare no conflict of interest.

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