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Multi-parameter characterization of indoor air quality in a medical marijuana cultivation facility in Oklahoma: a pilot study of occupational exposure determinants

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Abstract

The legal cannabis industry is expanding rapidly across the United States, yet indoor air quality (IAQ) characterizations of cultivation facilities remain scarce. Oklahoma's medical marijuana program grew to over 7,300 commercial licenses and 380,000 registered patients by 2023, but no published study has characterized occupational exposures within the state's cultivation facilities. Cannabis workers face poorly understood respiratory hazards, including elevated carbon dioxide (CO_2) from plant respiration, particulate matter (PM) from cultivation activities, volatile organic compounds (VOCs), and extreme thermal and humidity conditions. This pilot study addresses this critical knowledge gap. We conducted continuous monitoring (10 July to 1 August 2023) in a 2,000 ft^2 (approximately 186 m^2) heating, ventilation, and air conditioning (HVAC)-equipped indoor medical cannabis cultivation facility in Central Oklahoma housing approximately 900 plants. The monitored room used an approximately 12-h light:12-h dark photoperiod, intermittent supplemental CO_2, and a continuously operating single-zone HVAC system. Seven instruments were deployed across 3 spatial zones at breathing zone height (1.5 m): 3 Aranet4 nondispersive infrared (NDIR) CO_2 sensors, 2 TSI AirAssure (8144) multi-parameter monitors (CO_2, CO, NO_2, O_3, SO_2, total volatile organic compound [tVOC], size-resolved PM), and 2 PurpleAir PA-II-FLEX dual-channel particle counters. Approximately 113,000 quality-controlled records were analyzed. CO_2 concentrations exhibited a photoperiod-linked diurnal pattern driven by the plant light/dark cycle, with Aranet4 means ranging from 979 to 1,086 ppm and maxima exceeding 2,200 ppm. Elevated nighttime CO_2 was consistent with the combined influence of plant metabolism, intermittent CO_2 enrichment, and ventilation dynamics; worker respiration at night was unlikely to be the dominant explanation because workers generally left the room after lights were turned off. Median $PM_{2.5}$ concentrations were low (1.4 to 3.1 μg/m^3), but episodic spikes reached 5,000 to 35,000 μg/m^3. The largest daytime PM excursion coincided with an in-flower canopy-maintenance event, which was trimming, defoliation, or canopy maintenance. Mean tVOC concentrations

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reached 3.61 mg/m^3, and ethanol proxies exceeded 8,000 ppb at the 95th percentile. Temperature and relative humidity frequently reached levels that may increase heat stress and may also influence sensor performance under high-humidity conditions. This pilot study demonstrates that indoor medical cannabis cultivation facilities can present a complex, multi-hazard exposure environment involving CO_2 enrichment and photoperiod-linked CO_2 variability, episodic PM excursions, VOCs, and elevated heat and humidity. These findings highlight an urgent need for cannabis-specific occupational exposure research, facility ventilation guidance, activity-resolved monitoring, and worker health surveillance programs, particularly in states like Oklahoma where rapid industry growth has outpaced occupational health infrastructure.

Keywords cannabis cultivation, indoor air quality, occupational exposure, particulate matter, volatile organic compounds, medical marijuana

What's Important About This Paper

This study presents the first continuous, multi-parameter indoor air quality monitoring campaign in an Oklahoma Cannabis cultivation facility, a state with no cannabis-specific occupational health guidelines. The study found a photoperiod-driven carbon dioxide exposure pattern, extreme episodic fine particulate matter spikes, elevated total volatile organic compound concentrations, and thermal conditions frequently exceeding occupational thresholds. These findings establish a quantitative foundation for cannabis-specific ventilation standards and occupational exposure limits in a regulatory environment that has not kept pace with the industry's rapid expansion.

Introduction

The legal cannabis industry has undergone extraordinary expansion in the United States over the past decade. As of 2024, recreational cannabis is legal in over 20 states, medical cannabis is permitted in nearly 40 states, and the industry supports an estimated 250,000 jobs nationally across cultivation, processing, and retail operations (Simpson 2020). Federal policy may also shift, as the Drug Enforcement Administration has issued notices related to proposed rescheduling of marijuana into Schedule III of the Controlled Substances Act (Drug Enforcement Administration 2026). This evolving legal and regulatory landscape may alter production scale, licensing models, research access, and occupational health oversight. In most states, industry growth has outpaced the development of occupational health and safety frameworks tailored to the unique hazards encountered by cannabis workers. Indoor cannabis cultivation, in particular, creates sealed or semi-sealed microenvironments engineered to optimize plant growth, often at the expense of worker comfort and respiratory health.

Oklahoma presents a uniquely compelling case study for examining occupational exposures in cannabis cultivation. Following the passage of State Question 788 in June 2018, Oklahoma's medical marijuana program expanded at a pace that surprised even industry analysts. By 2023, the Oklahoma Medical Marijuana Authority (OMMA) had issued over 7,300 commercial licenses (including more than 1,800 dispensaries), and more than 380,000 Oklahomans (approximately 10% of the state population) were registered as medical marijuana patients, making it one of the most permissive and heavily utilized programs in the nation (OMMA 2023). In fiscal year 2023, OMMA completed 9,566 inspections, and the state collected hundreds of millions of dollars in cannabis excise tax revenue. A study commissioned by OMMA found that the state had 32 times more regulated medical cannabis than necessary to meet patient demand (OMMA 2023), reflecting an extraordinary proliferation of cultivation facilities across the state.

Despite this explosive growth, no published study has characterized the indoor air quality or occupational exposure conditions within Oklahoma's cannabis cultivation facilities (CCFs). This is a significant gap, because Oklahoma's regulatory environment, climate, and facility characteristics differ markedly from the states (eg Washington, Colorado, Minnesota) where the limited existing research has been conducted (Couch et al. 2019; Wang et al. 2019; Sack et al. 2020; Silvey et al. 2020; Simpson 2020). Oklahoma's hot, humid summers (mean July temperatures in Central Oklahoma exceeding 33 °C with dewpoints frequently above 21 °C) compound indoor heat stress in grow rooms that already operate at elevated temperatures and humidities. Furthermore, Oklahoma's initially low barriers to entry attracted many small-scale operators who may lack the engineering controls and heating, ventilation, and air conditioning (HVAC) sophistication of larger commercial facilities in states with more established industries. The state's 2022 moratorium on new grower licenses, extended through August 2026, reflects recognition of market oversaturation, but the thousands of licensed facilities that remain in operation continue to employ workers whose exposure profiles are entirely uncharacterized.

Indoor CCFs present a constellation of occupational exposure concerns that distinguish them from other agricultural and horticultural operations. First, CCFs may supplement CO_2 to enhance photosynthetic yield, and CO_2 concentrations may also vary with photoperiod-dependent plant metabolism, ventilation patterns, and cultivation-room control strategies (Couch et al. 2019; Wang et al. 2019). Second, cultivation and plant-maintenance activities can generate episodic particulate matter (PM) that may include organic dusts, fungal spores, soil or substrate particles, and plant-derived allergens (Sack et al. 2020; Silvey et al. 2020). Third, cannabis plants emit complex mixtures of biogenic volatile organic compounds (BVOCs), predominantly monoterpenes and sesquiterpenes, that can reach concentrations in task zones involving direct plant manipulation (Samburova et al. 2019; Silvey et al. 2020). Fourth, the warm, humid conditions required for optimal plant growth can create thermal stress, increase moisture loads, and promote microbial proliferation (Martyny et al. 2013).

Recent literature on indoor air quality in CCFs remains very limited and is concentrated in a small number of states. Martyny et al. (2013) characterized air quality in illegal indoor grow operations in Colorado, reporting terpene concentrations of 50 to 100 ppb and documenting the presence of fungal spores and pesticide residues. Samburova et al. (2019) measured BVOCs in 4 licensed commercial CCFs in Nevada, finding concentrations ranging from 21 to 290 ppb under typical conditions and exceeding 1,000 ppb when ventilation was restricted. Silvey et al. (2020) conducted the first task-specific occupational exposure assessment in 2 indoor cannabis facilities in Washington State, reporting mean PM mass concentrations of 42 to 60 $\mu g/m^3$ across grow, trim, and pre-roll task zones, with terpene mass concentrations reaching a mean of 36 mg/m^3 during trimming. In a complementary health study at the same Washington facility, Sack et al. (2020) documented a high prevalence of work-related respiratory symptoms (65%), including cough (48%), wheeze (16%), and chest tightness (26%), with 42% of workers meeting criteria for asthma. A National Institute for Occupational Safety and Health (NIOSH) Health Hazard Evaluation at a Minnesota medical cannabis facility identified diacetyl, 2,3-pentanedione, and more than 200 fungal taxa in the occupational environment (Couch et al. 2018, 2019, 2020). The Occupational Safety and Health Administration (OSHA) Colorado offices launched a Local Emphasis Program targeting cannabis facilities in 2024, driven by workplace fatalities and prior inspections, underscoring the enforcement gap in this sector (OSHA 2024). However, no comparable studies or enforcement programs exist for Oklahoma.

Most studies relied on short-duration or single-visit sampling campaigns, which fail to capture the temporal dynamics inherent to CCF operations, particularly the diurnal oscillation between light and dark cycles that fundamentally alters the indoor chemical and thermal environment. Furthermore, no published study has simultaneously deployed multiple sensor platforms across spatial zones within a single CCF to characterize both intra-room variability and inter-sensor agreement. The distinction between background (steady-state) conditions and episodic task-driven excursions has also been underexplored. Finally, most of occupational exposure research in CCFs comes from only 3 states (Washington, Colorado, and Minnesota); Oklahoma and other major cannabis markets remain entirely unrepresented.

The present pilot study addresses these gaps by conducting the first multi-week, spatially resolved, multi-parameter continuous monitoring campaign in an active medical marijuana cultivation facility in Oklahoma. Our objectives were to: (i) characterize the temporal patterns of CO_2, $PM_{2.5}$, gaseous pollutants (CO, NO_2, O_3, SO_2, total volatile organic compound [tVOC]), temperature, and relative humidity over a continuous multi-week deployment; (ii) evaluate spatial heterogeneity across 3 monitoring zones within the facility; (iii) identify and characterize episodic PM excursions potentially associated with cultivation activities and/or facility operations; (iv) assess inter-sensor and cross-platform agreement to inform future monitoring strategies; and (v) contextualize findings within the existing literature on occupational exposures in cannabis cultivation settings from other states.

Materials and methods

Study setting

This pilot study was conducted in an indoor medical marijuana cultivation facility located in Central Oklahoma. The facility had a floor area of approximately 2,000 ft^2 (186 m^2) and housed approximately 900 cannabis plants during an early-to-mid flowering monitoring period.

Based on facility-provided operational context, the crop was in early flowering from 10 July to mid-July, progressed through the early-to-mid flowering transition through 27 July, and continued into mid-flowering through 1 August (Table S1). A trimming, defoliation, or canopy-maintenance event occurred on 27 July during flowering, and this event was in-flower canopy maintenance rather than harvest trimming. The grow room was operated under an approximately 12-h light:12-h dark photoperiod, although exact light-on and light-off times varied somewhat from day to day. Supplemental CO_2 was used intermittently, but the exact dosing dates, dosing times, release rates, or target set points were available to the research team. The facility was served by a continuously operating, single-zone HVAC system, with supply air delivered near the middle of the room. Detailed HVAC specifications, outdoor-air fraction, return-air configuration, and feedback-control settings for CO_2, temperature, or relative humidity were not available. No dehumidifier was used. Pesticides were applied through an automatic plant-level application system, although exact application timing was not available to the research team.

A single entry door was located at the lower left of the facility (Fig. 1). The monitoring campaign was conducted during July and August 2023, coinciding with the peak of Oklahoma's summer heat season, when outdoor ambient temperatures in Central Oklahoma routinely exceed 35 °C and dewpoints frequently surpass 21 °C.

Instrumentation and deployment

Seven monitoring instruments were deployed across 3 spatial zones (left wall, center, right wall), each positioned at approximately 1.5 m above ground level, corresponding to the approximate breathing zone height for standing workers (Fig. 1, Table 1). Sensor locations were selected to characterize side-to-side and center-room spatial variation while remaining near plant rows and worker-accessible areas and avoiding interference with routine cultivation activities. Instruments were mounted using available room structures to maintain stable positioning during field deployment (Fig. S1). The TSI AirAssure (8144) monitors were secured to vertical plant-support stakes or posts using zip ties and positioned near the plant canopy. PurpleAir PA-II-FLEX monitors were placed on existing side-wall ledges or fixed room surfaces adjacent to plant rows. Aranet4 CO_2 monitors were placed on horizontal lighting supports or similar stable structures above or near the canopy. Power cables were routed along nearby posts, ledges, or support structures to minimize instrument movement, reduce trip or obstruction risks, and avoid interference with plant management. The instrument array comprised 3 sensor types selected to provide complementary measurements of key IAQ parameters:

- Aranet4 NDIR CO_2 sensors (CO2_01, CO2_02, CO2_03): Three low-cost NDIR sensors recording CO_2, temperature, relative humidity, and barometric pressure at 5-min intervals (Fig. S1). CO2_01 (left wall) and CO2_02 (right wall) monitored from 10 July to 24 July 2023 (4,218 records each after quality control); CO2_03 (center) monitored from 10 July to 17 July (2,256 records).
- TSI AirAssure (8144) monitors (TSI-01, TSI-02): Two multi-parameter instruments recording $PM_{2.5}$, PM_{10}, CO_2, CO, NO_2, O_3, SO_2, tVOC, temperature, relative humidity, and barometric pressure at 1-min intervals. TSI-01 was deployed at the left wall (20,896 records, 10 July to 1 August); TSI-02 at the right wall (31,074 records, 10 July to 1 August) (Fig. S1).
- PurpleAir PA-II-FLEX particle counters (PA-01, PA-02): Two dual-channel (Channels A and B) laser scattering particle counters measuring PM_1, $PM_{2.5}$, and PM_{10} at 2-min intervals. PA-01 was deployed at the left wall (14,613 records, 11 July to 1 August); PA-02 at the right wall (16,157 records, 10 July to 1 August) (Fig. S1). The dual-channel configuration permits internal consistency checks.

Prior to field deployment, sensor quality assurance was conducted within the constraints of a rapid-access pilot study. Because access to active CCFs is difficult to obtain and can be withdrawn quickly, the research team deployed the available monitors immediately after site permission was granted. All instruments were new or recently purchased and were within approximately 6 mo of manufacturer calibration or factory release at the time of deployment. Before installation, instruments were inspected for proper operation, clock synchronization, data logging, power supply stability, and plausible

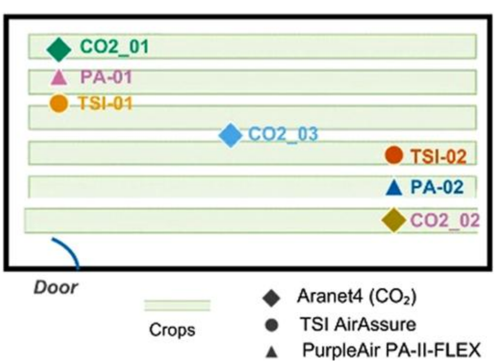

Figure 1 Schematic of instrument placement within the medical cannabis cultivation facility.

Table 1 Summary of indoor air quality monitoring instruments deployed during the monitoring campaign.

Sensor ID	Instrument	Sensor type	Location	Parameters measured[a]	Interval (min)	Monitoring period
CO2_01	Aranet4	NDIR CO_2	Left wall	CO_2, T, RH, P	5	10 Jul, 24 Jul
CO2_02	Aranet4	NDIR CO_2	Right wall	CO_2, T, RH, P	5	10 Jul, 24 Jul
CO2_03	Aranet4	NDIR CO_2	Center	CO_2, T, RH, P	5	10 Jul, 17 Jul
TSI-01	BlueSky 8143	Multi-parameter	Left wall	$PM_{1/2.5/4/10}$, CO_2, CO, NO_2, O_3, SO_2, tVOC, T, RH	1	10 Jul, 1 Aug
TSI-02	BlueSky 8143	Multi-parameter	Right wall	$PM_{1/2.5/4/10}$, CO_2, CO, NO_2, O_3, SO_2, tVOC, T, RH	1	10 Jul, 1 Aug
PA-01	PA-II-FLEX	Laser scattering	Left wall	$PM_{1/2.5/10}$ (dual), T, RH, Gas index	2	11 Jul, 1 Aug
PA-02	PA-II-FLEX	Laser scattering	Right wall	$PM_{1/2.5/10}$ (dual), T, RH, Gas index	2	10 Jul, 1 Aug

[a]T, temperature; RH, relative humidity; P, barometric pressure; PM, particulate matter; *N*, number of records after quality control filtering.

baseline readings. No field correction factors were applied (Barkjohn et al. 2021), as the study objective was to characterize temporal patterns, spatial contrasts, and episodic excursions rather than to generate regulatory-equivalent concentrations.

Statistical analysis

Descriptive statistics (mean, standard deviation, median, percentiles, range) were computed for all parameters by sensor (Table 2). Skewness and kurtosis were calculated for PM and gaseous pollutant distributions to characterize departure from normality (Table S2). Diurnal patterns were examined by pooling data across sensors within each instrument family and computing hourly box-plot summaries (Fig. 2). Pearson correlation coefficients were computed on hourly averaged CO_2 data across all 5 sensors to assess inter-sensor and cross-platform agreement (Table S3, Fig. 3). Complete-case correlations and timestamp-offset sensitivity analyses were conducted to evaluate the influence of nonoverlapping monitoring periods and UTC (coordinated universal time)-to-local timestamp conversion on cross-platform CO_2 interpretation (Table S4, Figs. S8 and S9). The largest $PM_{2.5}$ event hours were summarized with coincident TSI CO_2 concentrations to contextualize the 27 July event (Table S5, Fig. S10). Bland–Altman analysis was applied to the dual PurpleAir channels to evaluate intra-sensor agreement (Fig. S6). Cross-platform $PM_{2.5}$ comparisons between co-located TSI and PurpleAir sensors used log-transformed hourly means with ordinary least-squares regression (Fig. S7). All analyses were conducted in R (RStudio 2022).

Results

Carbon dioxide

CO_2 concentrations across all 5 sensors revealed a pervasive and distinctive diurnal pattern broadly aligned with the facility photoperiod and cultivation-room operation (Fig. 4). Mean CO_2 concentrations measured by the 3 Aranet4 NDIR sensors ranged from 979 ppm (CO2_03, center) to 1,086 ppm (CO2_01, left wall), with maximum values of 2,214 to 2,290 ppm (Table 2). The TSI AirAssure monitors recorded lower means (883 ppm for TSI-01, 897 ppm for TSI-02), possible due to their longer monitoring period and slightly different operational conditions later in the campaign (Table 1).

The diurnal CO_2 signature was most clearly resolved by the Aranet4 sensors (Fig. 4a). The facility used an approximately 12-h light:12-h dark photoperiod, but exact light-on and light-off times varied somewhat from day to day. During light periods, photosynthetic uptake, intermittent CO_2 enrichment, and HVAC operation likely interacted to shape room concentrations. During dark periods, CO_2 tended to accumulate and reached peak values in the late night or early morning hours (Figs. 2a and 4). However, because exact CO_2 dosing logs, HVAC control records, and outdoor-air exchange rates were unavailable, the nighttime pattern should be interpreted as the combined result of plant metabolism, intermittent supplemental CO_2, and ventilation dynamics rather than as direct evidence of plant dark respiration alone. Several readings exceeded 1,000 ppm, a commonly used general indoor-air reference value from the American Society of

Table 2 Descriptive statistics of key indoor environmental quality parameters measured by all sensors during the monitoring campaign. Values represent the full monitoring period for each sensor.

Sensor	N	Mean	SD	Median	P25	P75	Min	Max
CO_2 (ppm)								
CO2_01	4,218	1,085.7	325.2	1,136.0	821.2	1,211.0	275	2,290
CO2_02	4,218	1,038.0	314.9	1,070.5	787.0	1,146.0	225	2,210
CO2_03	2,256	979.2	356.0	1,041.0	691.0	1,151.2	241	2,214
TSI-01	20,896	882.8	213.2	912.0	726.0	988.0	485	1,690
TSI-02	31,074	897.3	269.3	935.0	697.0	1,014.0	188	2,036
$PM_{2.5}$ (μg/m^3)								
TSI-01	20,896	159.1	1,921.4	2.0	2.0	3.0	0	34,953
TSI-02	31,074	184.7	1,835.1	2.0	1.0	3.0	0	30,070
PA-01 (Ch.A)	14,613	36.5	240.7	3.1	1.5	4.9	0.0	4,655.5
PA-01 (Ch.B)	14,613	36.8	269.1	2.6	1.1	4.3	0.0	4,715.2
PA-02 (Ch.A)	16,157	31.0	264.0	1.4	0.3	2.8	0.0	5,007.8
PA-02 (Ch.B)	16,157	33.7	254.2	3.0	1.6	4.7	0.0	5,009.0
Temperature (C)								
CO2_01	4,212	25.7	3.0	24.3	23.7	26.7	21.0	38.0
CO2_02	4,216	27.9	4.5	28.4	23.8	30.9	22.9	41.2
CO2_03	2,256	27.8	4.2	27.6	24.0	31.1	23.1	40.5
TSI-01	20,896	23.3	2.9	23.5	22.7	24.1	16.9	34.0
TSI-02	31,074	25.9	3.6	25.4	23.5	27.7	20.3	39.6
Relative humidity (%)								
CO2_01	4,212	76.7	13.4	75.0	64.0	90.0	54	97
CO2_02	4,216	73.7	17.9	68.0	57.0	93.0	46	99
CO2_03	2,256	71.8	16.0	68.0	57.0	86.0	48	99
TSI-01	20,896	81.6	12.9	77.0	72.0	98.0	48	100
TSI-02	31,074	77.1	15.1	71.0	65.0	93.0	52	100

$PM_{2.5}$ statistics include extreme spike events that substantially inflate the mean and SD. Median values are more representative of typical indoor conditions. CO2_01 = Aranet4 (left wall), CO2_02 = Aranet4 (right wall), CO2_03 = Aranet4 (center). Ch.A and Ch.B refer to dual PurpleAir laser channels.

Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), although this value is not an enforceable occupational exposure limit and was not developed specifically for cultivation rooms.

An overlay of all 5 CO_2 sensors on a common hourly averaged time axis (Fig. 4c) demonstrated strong concordance among the Aranet4 cluster throughout the overlapping monitoring period (10 to 17 July). Inter-sensor correlations within the Aranet4 family were near-perfect ($r > 0.996$ to 0.999; Table S3, Fig. 3), indicating minimal spatial heterogeneity in CO_2 across the 2,000 ft^2 grow room for this well-mixed gas. The 2 TSI sensors were similarly well-correlated ($r = 0.994$). Nominal cross-platform correlations between Aranet4 and TSI sensors were lower ($r = 0.18$ to 0.45), reflecting the partly nonoverlapping monitoring periods, different timestamp conventions, and distinct NDIR sensor characteristics. Complete-case and timestamp-offset sensitivity analyses further showed that Aranet4-TSI correlations were highly sensitive to the restricted overlap window and assumed time alignment (Table S4, Figs. S8 and S9), so cross-platform CO_2 correlations were interpreted as a sensitivity finding rather than as evidence of spatial heterogeneity.

Particulate matter

$PM_{2.5}$ concentrations displayed a strongly right-skewed distribution with extreme episodic excursions superimposed on a low background (Table 2, Fig. 5). Median $PM_{2.5}$ values were consistently low across all sensors and channels: 2.0 μg/m^3 for both TSI sensors, and 1.4 to 3.1 μg/m^3 across PurpleAir channels. These medians suggest that under quiescent conditions, the HVAC-equipped room maintained relatively low particle concentrations. Yet, these fixed-location sensor data should not be

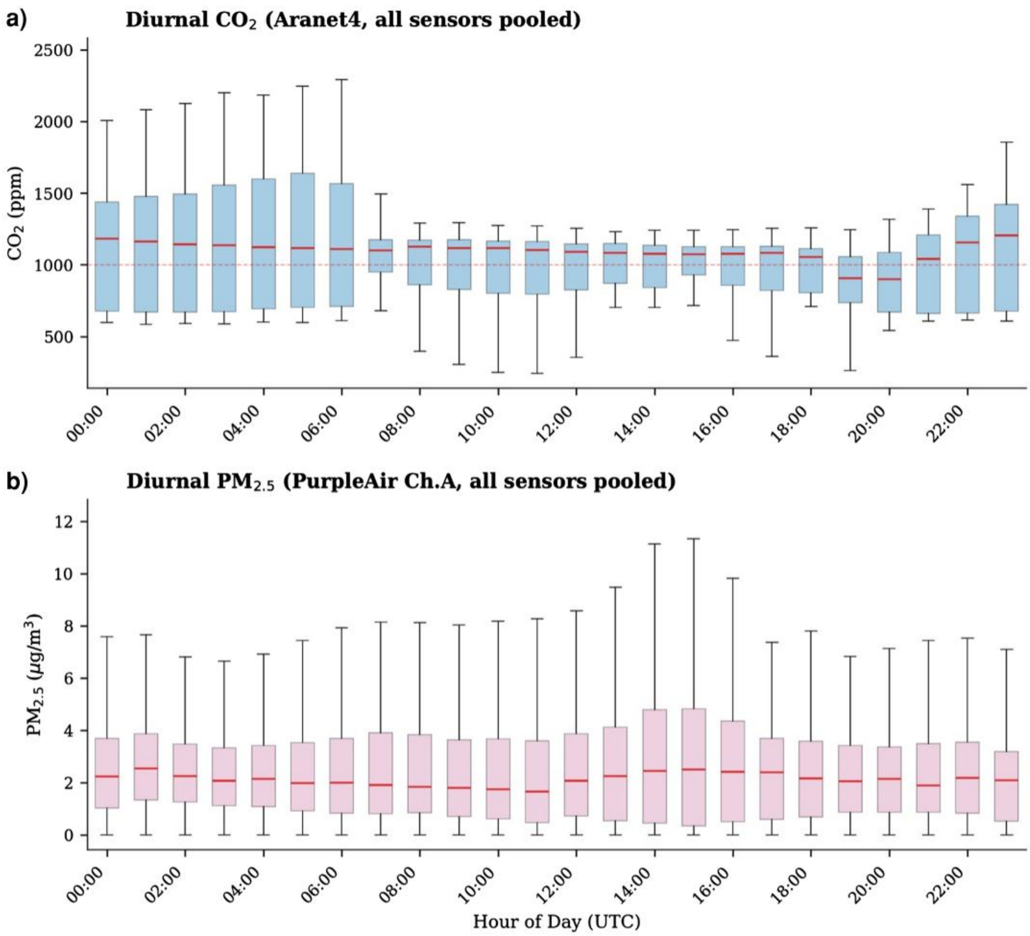

Figure 2 Diurnal box plots of a) CO_2 (Aranet4 sensors pooled, local time) and b) $PM_{2.5}$ (PurpleAir Channel A, sensors pooled, UTC). Boxes span P25 to P75, red lines indicate medians, whiskers extend to the nonoutlier range. The dashed line in panel (a) indicates the ASHRAE 1,000 ppm threshold.

interpreted as personal exposures or as direct compliance measurements for OSHA PM standards. $PM_{2.5}$ was log-transformed because particle concentrations were highly right-skewed with extreme episodic spikes across several orders of magnitude, whereas CO_2 was analyzed on the original scale because values were bounded in a narrower range and the goal was inter-sensor linear agreement.

However, the episodic spikes were distinct. TSI-01 recorded a maximum $PM_{2.5}$ of 34,953 μg/m^3, and TSI-02 reached 30,070 μg/m^3 (Table 2). The PurpleAir sensors captured peak values in the range of 4,656 to 5,010 μg/m^3 across channels. These extreme excursions inflated the arithmetic means to 159 to 185 μg/m^3 for the TSI sensors and 31 to 37 μg/m^3 for the PurpleAir sensors, values approximately 50 to 90 times the corresponding medians. The skewness of $PM_{2.5}$ distributions ranged from 8.3 to 14.2, and kurtosis from 74 to 225 (Table S2), confirming the extreme leptokurtic character of these distributions.

The time series of $PM_{2.5}$ hourly means (Figs. 3b and 5a) revealed that spikes were discrete, short-lived events, typically lasting minutes to a few hours, and were captured simultaneously (or near-simultaneously). The largest event occurred during daytime hours on 27 July, when TSI-01 recorded an hourly maximum $PM_{2.5}$ concentration of 34,953 μg/m^3 and TSI-02 recorded an hourly maximum of 26,982 μg/m^3 (Table S5, Fig. S10). Facility-provided operational context indicates that this event coincided with in-flower canopy maintenance, such as trimming, defoliation, or canopy management. Facility information also indicated that pesticides were applied through an automatic plant-level system, but exact application timestamps were not available. No formal worker task log, tag-in/tag-out record, soil-handling log, or equipment-operation log was available. This limitation reflects the rapid-access nature of the pilot study. Similar patterns were observed for larger size fractions (PM_4, PM_{10}; Table S2, Fig. S5), with even more

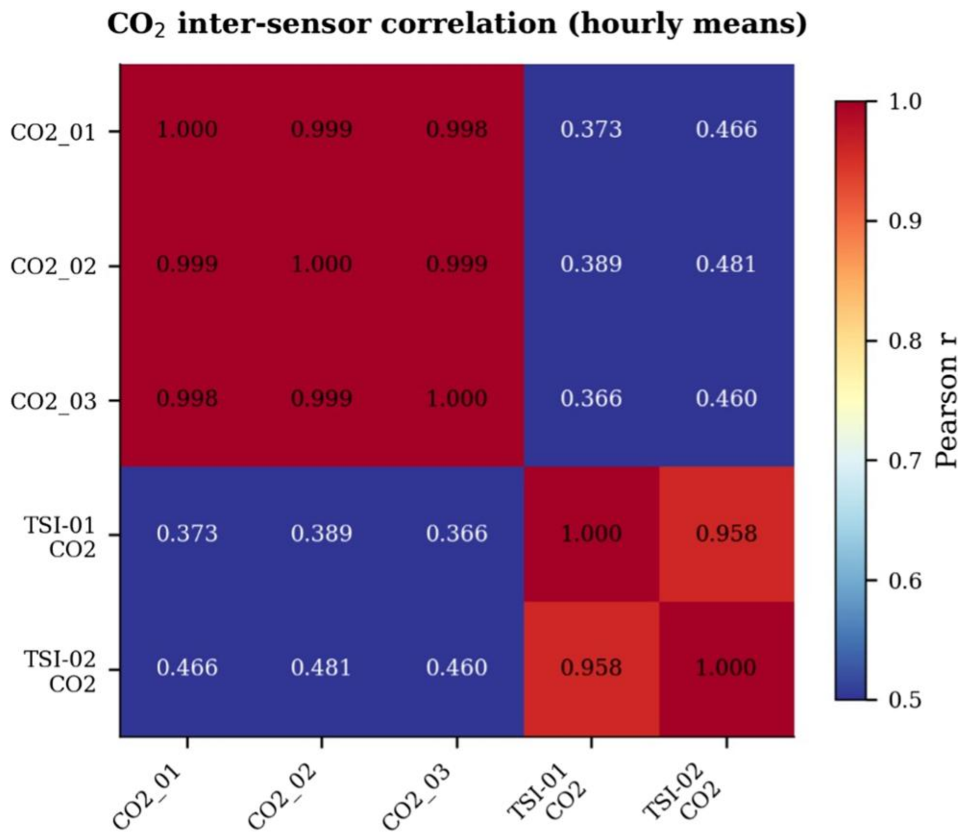

Figure 3 Pearson correlation heatmap for CO_2 measurements across all 5 sensors (hourly means).

extreme maxima (eg PM_{10} up to 63,913 µg/m^3 at TSI-01), suggesting that at least some events included a coarse-mode component.

Gaseous pollutants and volatile organic compounds

The TSI AirAssure (8144) monitors provided continuous measurements of several gaseous pollutants (Table S2, Fig. S3). Carbon monoxide (CO) concentrations were generally low, with medians of 1.4 ppm (TSI-01) and 2.2 ppm (TSI-02), well below the NIOSH recommended exposure limit (REL) of 35 ppm as an 8-h time-weighted average (NIOSH 2020). Maximum values of 17.6 and 19.4 ppm were observed. Because no combustion source or specific CO-generating activity was confirmed, these peaks were interpreted cautiously as sensor-based excursions that require confirmation with reference or calibrated occupational instruments in future studies.

Nitrogen dioxide (NO_2) showed markedly different profiles between the 2 sensors. TSI-01 recorded a median of 41 ppb (mean 49 ppb), while TSI-02 recorded a median of 0 ppb (mean 7 ppb), a spatial discrepancy that may reflect localized emission sources, differences in proximity to ventilation intakes, or sensor cross-sensitivity (Fig. S3b). Ozone (O_3) was essentially undetectable at TSI-01 (median 0 ppb) but showed a modest presence at TSI-02 (median 11 ppb, mean 16 ppb; Fig. S3c). The facility did not report the use of ozone generators or ozone-based disinfection equipment during sampling. Therefore, the O_3 results were interpreted as screening-level measurements rather than evidence of a confirmed ozone source. Sulfur dioxide (SO_2) was detected at both locations (medians of 10 and 20 ppb), at levels below occupational exposure limits.

tVOC concentrations were notably higher at TSI-02 (mean 3.61 mg/m^3, median 1.34 mg/m^3) than at TSI-01 (mean 1.42 mg/m^3, median 1.02 mg/m^3), with 95th percentile values reaching 3.72 and 15.19 mg/m^3 respectively. The ethanol-equivalent VOC metric (EtOH) followed a parallel pattern, with TSI-02 recording a mean of 1,918 ppb (95th percentile: 8,081 ppb) compared to 757 ppb (95th percentile: 1,978 ppb) at TSI-01 (Fig. S3d). Because the TSI tVOC measurement is based on a

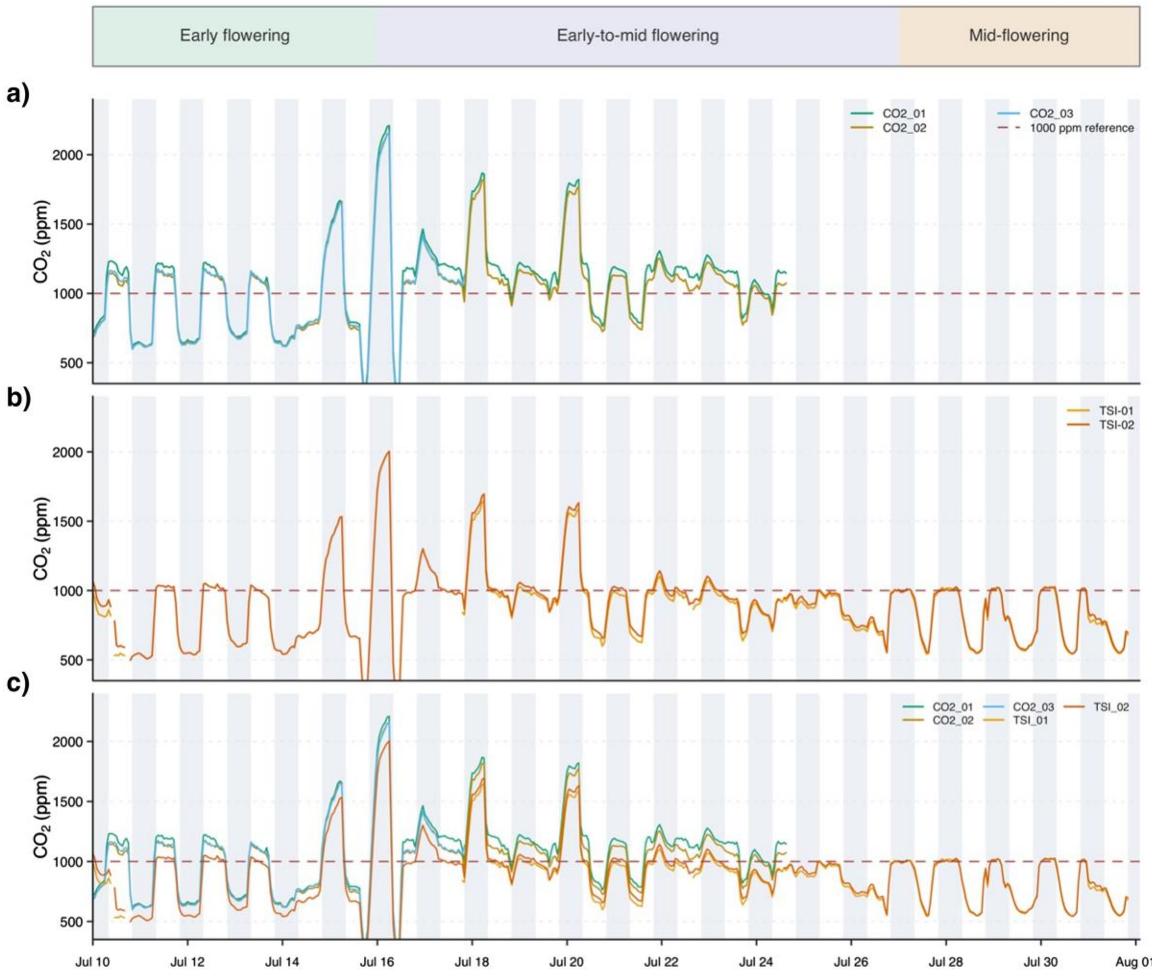

Figure 4 Time-resolved CO_2 concentrations. Hourly CO_2 concentrations are shown for a) Aranet4 monitors, b) TSI AirAssure monitors, and c) all paired CO_2 sensors from 10 July to 1 August. Gray bands indicate approximate dark periods, and the upper timeline shows the inferred crop-stage progression from early flowering to mid-flowering. The dashed horizontal line indicates 1,000 ppm as a reference level.

broadband metal-oxide sensor rather than compound-specific sampling, these results should be interpreted as relative indicators of VOC burden and temporal variability, not as speciated terpene concentrations.

Temperature and relative humidity

Indoor temperatures across all sensors ranged from 16.9 °C to 41.2 °C, with means of 23 to 28 °C depending on sensor placement (Table 2, Fig. S2a). The highest temperatures were recorded by CO2_02 (right wall, mean 27.9 °C, max 41.2 °C) and CO2_03 (center, mean 27.8 °C, max 40.5 °C). OSHA and NIOSH heat guidance identifies a heat index of 80°F (26.7 °C) or higher as the beginning of a warning category for occupational heat stress, although heat index, workload, clothing, acclimatization, radiant heat, and access to rest and water are needed for a full heat-stress assessment (OSHA 2022). The July and August sampling period in Central Oklahoma represents a thermally challenging season for indoor cultivation operations, as the HVAC system would contend with grow-light heat loads, high plant moisture loads, and extreme outdoor ambient temperatures.

Relative humidity was consistently elevated, with means of 72% to 82% across sensors and maximum values reaching 99% to 100% (Table 2, Fig. S2b). These conditions exceed common indoor comfort and moisture-control reference ranges and may promote microbial growth, as documented in prior cannabis cultivation investigations and NIOSH evaluations identifying

Figure 5 Time-resolved $PM_{2.5}$ concentrations. Hourly $PM_{2.5}$ concentrations from a) TSI AirAssure and b) PurpleAir PA-II-FLEX monitors from 10 July to 1 August. The upper timeline indicates the inferred flowering-stage progression. The dashed vertical line marks the reported 27 July in-flower trimming, defoliation, or canopy-maintenance event.

fungal taxa in CCFs (Martyny et al. 2013; Couch et al. 2018). The facility did not use a dehumidifier. With approximately 900 plants transpiring in a 2,000 ft^2 space, the moisture load was substantial, and the combination of high temperature and high humidity may increase physiological heat burden on workers during daytime cultivation tasks. High humidity also has implications for sensor performance, particularly for electrochemical gas sensors, metal-oxide VOC sensors, and optical particle sensors, and therefore supports cautious interpretation of absolute gas and PM concentrations.

Inter-sensor agreement and cross-platform comparison

The Pearson correlation heatmap (Fig. 3) revealed a hierarchical structure of inter-sensor agreement for CO_2 measurements. Within the Aranet4 cluster, pairwise correlations exceeded $r = 0.996$ (Table S3), demonstrating exceptional agreement among the 3 low-cost NDIR sensors deployed at different spatial positions within the 2,000 ft^2 room. The 2 TSI AirAssure sensors were similarly well-correlated ($r = 0.994$). The Aranet4 scatter plots (Fig. S4) further confirmed linearity and minimal bias among the Aranet4 units during overlapping deployment periods. In contrast, complete-case and timestamp-offset sensitivity analyses (Table S4, Figs. S8 and S9) showed that cross-platform Aranet4-TSI correlation estimates depended strongly on the selected overlap window and temporal alignment, reinforcing the need for synchronized clocks and concurrent deployment in future multi-platform monitoring studies.

Cross-platform correlations between Aranet4 and TSI CO_2 sensors were lower ($r = 0.18$ to 0.45). These values should be interpreted cautiously because the platforms differed in calibration basis, response characteristics, timestamp conventions, and monitoring periods. After temporal alignment, the within-platform agreement was stronger than the between-platform agreement, supporting the use of consistent sensor families for interpreting temporal patterns in future studies. These findings do not constitute formal validation against reference instruments.

For $PM_{2.5}$, the Bland–Altman analysis of PurpleAir dual channels (Fig. S6) demonstrated good internal consistency within each sensor, with mean differences near zero and narrow limits of agreement. The cross-platform comparison between co-located TSI and PurpleAir sensors (Fig. S7) revealed moderate agreement on log-log axes, with both platforms capturing the same spike events, though quantitative discrepancies in absolute concentrations were evident. These discrepancies are consistent with differences in measurement principles, particle-size response, humidity sensitivity, and upper measurement range.

Discussion

CO_2: photoperiod-linked and facility-operation-linked exposure determinant

A key finding of this pilot study is the strong diurnal CO_2 fluctuation linked to the plant photoperiod and cultivation-room operation. The pattern is consistent with a combination of plant CO_2 uptake during light periods, plant respiration during dark periods, intermittent supplemental CO_2 use, and ventilation dynamics. Facility information indicated that workers generally left the room after lights were turned off, reducing the likelihood that nighttime worker respiration was the primary driver of sustained nighttime CO_2 elevation. However, because the facility did not provide exact CO_2 dosing records, light-on/light-off logs, HVAC trend data, outdoor-air fractions, or air-exchange rates, we cannot apportion the observed CO_2 pattern quantitatively among plant metabolism, enrichment, and ventilation. We therefore interpret the CO_2 results as evidence of a photoperiod-linked and facility-operation-linked exposure determinant, not as direct proof of plant dark respiration alone.

NIOSH reviews of cannabis-related health hazard evaluations have noted that CO_2 levels during enrichment in cannabis facilities are typically below 2,000 ppm and below the NIOSH REL of 5,000 ppm as an 8-h time-weighted average Our area-monitoring data remained below the NIOSH REL throughout the campaign. Nevertheless, concentrations exceeded common general indoor-air reference values during portions of the monitoring period, and concentrations above 1,500 ppm may be relevant for worker comfort, alertness, and symptom reporting in some indoor environments. These reference values are not cannabis-specific occupational exposure limits, and they should be interpreted as contextual benchmarks rather than regulatory standards for cultivation rooms.

This observed CO_2 pattern extends prior cannabis IAQ work by showing that a production grow room can exhibit substantial within-day CO_2 variability over a multi-week deployment. Prior studies have primarily focused on task-based PM, VOCs, bioaerosols, and respiratory symptoms, and few have reported continuous, spatially distributed CO_2 time series in cultivation rooms (Couch et al. 2020). Our findings support the need for future studies that integrate CO_2 monitoring with CO_2 enrichment logs, HVAC trend data, photoperiod records, nonidentifiable worker presence logs, and air-exchange measurements.

PM: low background, extreme deviations

The $PM_{2.5}$ results reveal a dual-regime exposure pattern: a low, relatively stable background punctuated by short-duration, high-magnitude excursions. The median $PM_{2.5}$ of 1.4 to 3.1 μg/m^3 suggests that under quiescent conditions, the HVAC-equipped room maintained low particle concentrations. This contrasts with the task-specific area PM concentrations reported by Silvey et al. (2020) in Washington State cannabis facilities, where mean PM concentrations of 42 to 60 μg/m^3 were recorded in grow, trim, and pre-roll task zones. The difference likely reflects our continuous monitoring approach, which captures long inactive periods, versus task-period sampling, which targets active work intervals.

The episodic PM spikes, reaching concentrations in the thousands to tens of thousands of μg/m^3, suggesting occupational attention despite their short duration. Because the TSI AirAssure $PM_{2.5}$ specification is stated up to 1,000 μg/m^3, the highest values should be interpreted as evidence of extreme particle events rather than as precise mass concentrations. The 27 July event provides useful operational context: it coincided with reported in-flower canopy maintenance and is more appropriately interpreted as trimming, defoliation, or canopy management during flowering than as harvest trimming or post-harvest processing (Table S5, Fig. S10). If such events occurred while workers were present, they could contribute to substantial acute inhalation doses, particularly in the absence of respiratory protection. The NIOSH Health Hazard Evaluation of a cannabis facility in Minnesota documented area airborne total particle concentrations averaging 3.4 mg/m^3 (range up to 20.5 mg/m^3) during a single 45-min grinding operation (Couch et al. 2018). Our data suggest that high-magnitude particle events may also occur in cultivation rooms during plant-maintenance activities, but the absence of formal activity logs prevents precise task attribution.

The ratio of PM_{10} to $PM_{2.5}$ during spike events (Table S2) indicates a substantial coarse fraction component, consistent with mechanical generation or resuspension of particles from plant material, substrate, surfaces, or other room activities (Fig. S5). This coarse-mode signature is characteristic of agricultural and horticultural dusts. Silvey et al. (2020) suggested that the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) for cotton dust (0.1 mg/m^3) might serve as a point of comparison for cannabis facilities pending development of cannabis-specific limits. However, $PM_{2.5}$ and PM_{10} sensor readings are not directly comparable to gravimetric total dust, inhalable dust, respirable dust, or cotton dust methods used for occupational compliance. Cannabis-specific standards may need to consider plant-derived allergens, fungal fragments, microbial contaminants, and potential proinflammatory properties of hemp or cannabis dust components (Zuskin et al. 1990).

VOCs, thermal stress, and the multi-hazard environment

The tVOC concentrations recorded in this study (means of 1.42 to 3.61 mg/m^3, 95th percentiles up to 15.19 mg/m^3) indicate a measurable VOC burden in the monitored grow room. The TSI AirAssure VOC sensor provides a broadband metal-oxide response rather than speciated terpene quantification, so direct comparison with GC-MS-based terpene studies is limited. The ethanol-equivalent values (means of 757 to 1,918 ppb, 95th percentiles reaching 8,081 ppb) are broadly consistent with the expectation that flowering cannabis rooms can contain substantial BVOC and VOC burdens, but they cannot be interpreted as compound-specific terpene concentrations. Future studies should pair continuous VOC sensors with time-integrated sorbent-tube sampling and GC-MS analysis for terpene speciation.

The spatial asymmetry in tVOC, with TSI-02 recording concentrations roughly 2.5 times higher than TSI-01, supports the value of multi-location monitoring but should not be overinterpreted as confirmed spatial variability in VOC emissions. Possible explanations include differences in plant density or development stage near the sensors, local air movement, HVAC supply and return patterns, proximity to automatic pesticide delivery components, sensor variability, or humidity-related effects on the VOC sensor. A single monitoring point in a grow room may therefore miss important temporal or spatial patterns, but future studies require calibrated and speciated VOC methods to quantify exposure gradients.

Temperature and humidity conditions might increase worker burden in cultivation rooms. At relative humidities approaching 100% and temperatures exceeding 35 °C, physiological heat strain may increase, particularly during physical tasks. These conditions are particularly challenging in Central Oklahoma during July and August, when outdoor temperatures frequently exceed 38 °C and add to indoor HVAC thermal load. The Colorado guide to worker safety in the cannabis industry (State of Colorado 2017), OSHA's National Emphasis Program on heat-related hazards (OSHA 2023), and Colorado's 2024 Local Emphasis Program for cannabis facilities all recognize indoor cultivation as a high-risk setting (Zimmer 2024). Our data shows that this Oklahoma facility experienced temperature and humidity conditions that may need heat-stress prevention measures, though this pilot study did not include workload, clothing, metabolic-rate, or worker symptom data. Oklahoma currently has no comparable state-level guidance or enforcement program specific to cannabis facilities.

Comparison with prior studies

This pilot study contributes to a small but growing body of literature on occupational exposures in CCFs, with the largest prior contributions from Washington State (Sack et al. 2020; Silvey et al. 2020), Colorado (Martyny et al. 2013; State of Colorado 2017; Wang et al. 2019), and Minnesota/NIOSH (Couch et al. 2018, 2020). To our best knowledge, this is the first study to report continuous multi-parameter IAQ monitoring data from a CCF in Oklahoma, and one of the first from the South-Central United States. The main contribution is not that the measured hazards are entirely unique, but that they occur together in a small cultivation room as a dynamic multi-hazard environment involving CO_2, PM, VOCs, heat, and humidity.

Oklahoma's cannabis industry context differs from those states in several important respects. First, the scale of the industry relative to the state's population has been unusually large that Oklahoma had more licensed cannabis businesses per capita than any other state (Baldwin et al. 2024). Second, the initially low barriers to entry meant that many operators, including the facility in this study, were small-scale operations in converted commercial or warehouse spaces, potentially with less sophisticated environmental controls than purpose-built facilities in more established markets. Third, Oklahoma's hot and humid summer climate imposes unique thermal and moisture-control loads on indoor cultivation. Fourth, there are no state-level cannabis-specific worker safety guidelines comparable to Colorado's comprehensive guide (State of Colorado 2017). This regulatory gap means that workers in small cultivation facilities may experience recognized occupational hazards without cannabis-specific exposure guidance, ventilation criteria, or health surveillance systems.

Compared with the Washington State studies (Silvey et al. 2020; Simpson 2020), our study differs in design and measured endpoints. Our baseline (median) $PM_{2.5}$ levels are lower than the task-specific concentrations reported by Silvey et al. (2020), suggesting the continuous monitoring design might dilute task-period excursions across long quiescent intervals. Our baseline median $PM_{2.5}$ levels were lower than task-specific concentrations reported by Silvey et al. (2020), but our episodic PM excursions demonstrate that short-duration events may be missed or overrepresented depending on sampling design. Our tVOC results are not directly comparable with speciated terpene measurements because the TSI AirAssure VOC sensor is broadband and nonspeciated. Together, these studies indicate that cannabis workplaces require both task-based personal sampling and continuous environmental monitoring.

Limitations

This pilot study was limited by its single-facility design, which restricts generalizability to other CCFs with different plant densities, photoperiods, ventilation systems, CO_2 enrichment practices, pesticide use, and work organization. The study was conducted under a rapid-access field deployment model, with facility access granted on short notice. Therefore, the team prioritized immediate area monitoring to capture a rare occupational setting rather than conducting worker observation, personal exposure sampling, or formal task-based exposure assessment. Fixed-location area monitors do not capture personal exposures, which may be higher during specific tasks or near emission sources. No health outcome data, symptoms, worker demographics, personal sampling measurements, formal activity logs, tag-in/tag-out records, CO_2 dosing logs, HVAC control records, outdoor-air supply rates, or pesticide application timestamps were available. The facility provided general operational information, including an approximate crop-stage timeline, an approximately 12-h light:12-h dark photoperiod, intermittent supplemental CO_2 use, continuous HVAC operation, daytime worker occupancy, and a 27 July in-flower canopy-maintenance event, but exact timing and control parameters were not disclosed. As a result, PM, CO_2, and gaseous pollutant excursions should be interpreted as area-level environmental patterns rather than task-specific exposure estimates.

Calibration and field validation were also limited. Although sensors were newly purchased, had recent manufacturer calibration, and underwent pre-deployment laboratory co-location checks, the study did not include full multi-point calibration against NIST-traceable reference instruments before and after field deployment, nor field co-location with regulatory-grade or research-grade instruments inside the facility. Therefore, measured concentrations should be interpreted as high-temporal-resolution screening data suitable for identifying temporal patterns, spatial differences, and episodic excursions, rather than as compliance-grade exposure measurements. Additional limitations include nonconcurrent monitoring periods across sensor types, which complicates cross-platform comparisons; use of a broadband, unspeciated TSI AirAssure VOC response rather than speciated terpene measurements; potential effects of temperature, relative humidity, cross-sensitivities, particle composition, and particle size distribution on sensor response; several short-duration PM events exceeding the stated TSI PM measurement range; and the absence of outdoor or reference background measurements, which precluded estimation of indoor-outdoor ratios.

Conclusions

This pilot study, conducted in a 2,000 ft^2 HVAC-equipped medical marijuana cultivation facility housing approximately 900 plants in Central Oklahoma during July and August 2023. The findings demonstrate a dynamic, multi-hazard environment characterized by photoperiod-linked CO_2 variability, generally low background PM concentrations interrupted by short-duration extreme excursions, notable VOC concentrations, and elevated temperature and relative humidity. Because the study relied on fixed-site area monitoring and lacked synchronized activity, CO_2 dosing, pesticide application, and HVAC operational records, the observed concentrations should be interpreted as environmental exposure determinants rather than direct measures of individual worker exposure or task-specific dose.

These findings support several priorities for research and occupational health practice. Future studies could combine continuous area monitoring with personal and task-based sampling, speciated VOC and bioaerosol measurements, nonidentifiable activity logs, crop-stage metadata, and synchronized HVAC, supplemental CO_2, and pesticide application records. Such information is needed to identify the sources of episodic exposures, characterize individual worker doses, and evaluate whether existing occupational exposure limits and control approaches are adequate for cannabis cultivation environments. Ventilation and environmental-control guidance might also account for the competing requirements of plant production and worker protection, including management of air exchange, supplemental CO_2, temperature, humidity, and pesticide application.

The cannabis cultivation industry in Oklahoma, and nationally, has grown faster than the regulatory science needed to protect its workforce. With no cannabis-specific occupational exposure limits, limited ventilation guidance for cultivation rooms, and few published exposure datasets from rapidly expanding state markets, workers and employers have limited evidence on which to base exposure-control decisions. Health surveillance should be considered for cannabis cultivation workers, particularly for respiratory, allergic, and heat-related outcomes. Oklahoma's large and rapidly evolving medical marijuana industry provides both an urgent justification and a practical setting for developing occupational health protections for this workforce.

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Supplementary material

Supplementary material is available at *Annals of Work Exposures and Health* online.

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Conflicts of interest

The authors declare no conflicts of interest.

Data availability

The environmental monitoring data of this study are available from the corresponding author upon reasonable request. Facility-identifying information and operational details are not publicly available to protect site confidentiality.

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