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Following the smell: terpene emission profiles through the cannabis life-cycle†

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Cannabis cultivation and processing are emerging sources of air pollutants, particularly malodorous volatile organic compounds (VOCs), yet uncertainties remain regarding their emission rates and chemical composition. Emission rates are typically the starting point for an air quality assessment; not addressing their uncertainty and chemical profile may lead to under/over estimation of impacts. This study aims to quantify terpene emissions from indoor cannabis operations in the Lower Fraser Valley, BC, Canada a region already affected by odorous sources and peak ozone concentrations in the summer due to imbalance of VOC and nitrogen oxides (NO_x) emissions. We assessed terpene concentration variability across activities, and evaluated their potential odor impacts during peak summertime. For this, we developed an automated gas chromatography sampling and processing protocol to measure concentrations of 22 key cannabis terpenes in (1) eight rooms of an indoor cultivation facility and (2) six rooms of a processing and extraction facility. Emission rates varied widely, ranging from 1.05×10^{-3} to 3.09×10^{-1} kg h^{-1}, with the highest emissions occurring during trimming (*i.e.*, buds' extraction). We observed substantial temporal variability; individual terpene concentrations fluctuated by up to 1500% depending on activity type and lighting conditions. Pearson correlation analysis revealed non-linear relationships between individual terpenes and total emissions, suggesting shifts in chemical composition during peak emissions. To assess odor implications, we conducted screening dispersion modeling for β-myrcene, a terpene considered a tracer of cannabis emissions. Of the 7560 dispersion scenarios evaluated, 88 exceeded the odor threshold under average emissions, increasing to 241 scenarios during peak trimming emissions. Because emission rates and chemical compositions vary significantly depending on activity type and conditions, and dispersion modeling results showed that average conditions are sufficient to cause odor episodes, it is important to characterize both the temporal and chemical profiles of terpene emissions in cannabis facilities to avoid mis-estimating their air pollution and odor impact. Given the growing industry and the potential for odor complaints and secondary air pollution impacts (*e.g.*, ozone formation), it is crucial to understand these emissions in detail. Policymakers, scientists, and industry stakeholders can use our findings to develop better mitigation strategies and inform environmental regulations.

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Environmental significance

With the recent cannabis legalization and decriminalization in the world, cannabis cultivation and processing facilities surged. Understanding their environmental impact is even more critical than before, including the variation in Biogenic Volatile Organic Compound (BVOC) emissions during the plant life-cycle. These emissions contribute to community complaints due to malodors, and potentially the formation of pollutants like ozone and secondary organic aerosols. This study shows that individual terpene emissions, driven by room conditions and activities, vary non-linearly with total BVOC emissions, challenging the assumption of a proportional chemical profile between emission baseline and emission peak. By introducing time-resolved monitoring methodology, this work can inform emission inventories and dispersion modeling, offering insights applicable to managing malodor impacts and air quality for the cannabis industry.

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† Electronic supplementary information (ESI) available: Methods: questionnaire; facilities information; GC-FID calibration data; discussion of sampling program; low-cost sensor data and calibration; light scanning; reactions kinetics data; dispersion modelling inputs. Results: time series plots for all rooms; tables with terpene variation per room. Terpenes correlation analysis. See DOI: https://doi.org/10.1039/d5em00253b

1 Introduction

As new jurisdictions have legalized the use and commercialization of cannabis for medical and recreational purposes,[1] there has been a surge of interest among researchers and regulators about the potential occupational and environmental impacts of the increased number and size of cannabis production facilities.[2] Those include greenhouse gases emissions,[3] land cover change and resources use,[4] depletion of natural systems,[5] and air quality.[6]

Most studies have focused on investigating Biogenic Volatile Organic Compound (BVOC) air emissions from cannabis cultivation[7–9] and found that the composition can vary by cannabis strain, life-cycle stage, and between indoor and outdoor environments. The main terpenes found to be emitted by plants are β-myrcene, (+/−)-limonene, terpinolene, α-pinene and β-pinene. Of these, β-myrcene has been identified as a potential tracer due to its higher fraction of the total BVOC emissions from cannabis plant, and its relative absence in ambient air and indoor air of homes.[10,11] To a lesser extent, cannabis processing has also been investigated[12,13] and it was found that activities that involve manipulation (*e.g.*, trimming and packing) have higher emissions of terpenes and particulate matter. A more detailed overview of these findings can be found at de Ferreyro Monticelli *et al.*[14]

The interest in BVOCs is partly motivated by their potential to form secondary organic aerosols (SOA) and ozone (O_3),[15] which contribute to degraded air quality. While cannabis plants emit more BVOCs per dry weight of plant than many crops,[14] modeling studies suggest that the overall low VOC emission rates from the industry relative to other sectors[16] contribute to a low impact on O_3 and $PM_{2.5}$ formation.[7,8,16]

Nevertheless, cannabis emissions can be odorous and can cause annoyance to communities living nearby facilities.[17] Although BVOCs are not the only chemicals responsible for the cannabis smell,[18–20] they contribute to the mix of odorous emissions.[21] Because odor impact is a major cause of complaints towards the cannabis industry,[22] it is important to understand the total amount and the chemical content of BVOC emissions to better predict odors downwind of cannabis facilities. Environmental impact assessments typically assume that the emissions from cannabis facilities are constant.[23–25] Yet, recent investigations suggest temporal variability in total BVOC emissions.[13,16]

In a previous review of the cannabis industry's air quality impacts, de Ferreyro Monticelli *et al.*[14] identified sixteen gaps that must be addressed to better understand the environmental impact of cannabis cultivation and processing. Of these include improving sampling methods to enable building more detailed emission inventories. Thus, the goals of this study were to (1) develop an automated GC-FID sampling protocol and (2) apply it in indoor rooms of a cannabis cultivation and a cannabis processing facility, and (3) investigate the temporal concentration profile and emissions of 22 terpenes. We sought to determine: (1) if the speciated-temporal profile varies significantly within a day, (2) what environmental and work factors contribute to any identified variation and (3) if the variation should be accounted for in emission inventories and community exposure investigation studies.

2 Methods

2.1 Study location and relevance

Our study is situated in the Lower Fraser Valley (LFV), BC, Canada, which comprises the districts of Metro Vancouver and the southwestern portion of the Fraser Valley Regional District. Home to ≈3.3 million people,[26] the LFV faces a range of air quality issues due to its emissions profile, complex terrain, and meteorology.[27–29] Previous research in the region focused on peak tropospheric ozone in the spring/summer (O_3),[30–38] particulate matter (PM) and secondary organic aerosols (SOA) formation and transport,[39–46] and BVOC and anthropogenic VOCs emissions.[47–52]

To a lesser extent, odors have been evaluated by recent studies using inverse dispersion modeling,[53] and mobile monitoring and citizen science.[54,55] Odors are now the main cause of air quality complaints in the region, and the contribution of the cannabis sector to odor reports has been noticeable.[56] For instance, in the municipality of Delta, cannabis-related odors account for 73% of submissions made to the Smell Vancouver initiative during the first year of operation.[55]

In this context, it is imperative to investigate emissions from cannabis operations in the LFV, as they may increasingly contribute to odor-related concerns and exacerbate air quality challenges in a region already burdened by complex emission sources and atmospheric dynamics.

2.2 Facility recruitment

We recruited facilities by advertising the study at industry conferences (*e.g.*, GROW EXPO 2022), by phone calls, by e-mails, and by referral from project partners (WorkSafe BC). Prospective participating facilities were asked to complete a questionnaire that addressed cultivation practices, facility management, and air emissions control technologies (Fig. S1–S13 of the ESI†). This protocol was approved by the University of British Columbia Office of Research Ethics, ID: H22-00450. We selected two facilities (named CCF for Cannabis Cultivation Facility and CPF for Cannabis Processing Facility) for this study, based on their market influence, type of operation, and their capacity to participate in logistical planning for sampling.

2.3 Facility details

The CCF is an approximately 4400 m^2 indoor cannabis cultivation facility licensed for cultivation for medical purposes, with a capacity for 24 500 kg per yr of cannabis plants in wet weight, making it a "standard cultivation" in Canada (>800 m^2 grow surface area[57]). We sampled the following cultivation and processing operations/rooms: mother (female plants prolonged in vegetative state), vegetative (3.5weeks $\leq t \leq$ 6 weeks old), growing (>6 weeks, we sampled shortly after propagation and when plants were mature), drying (where plants lose most of their water content, we sampled before and after plant

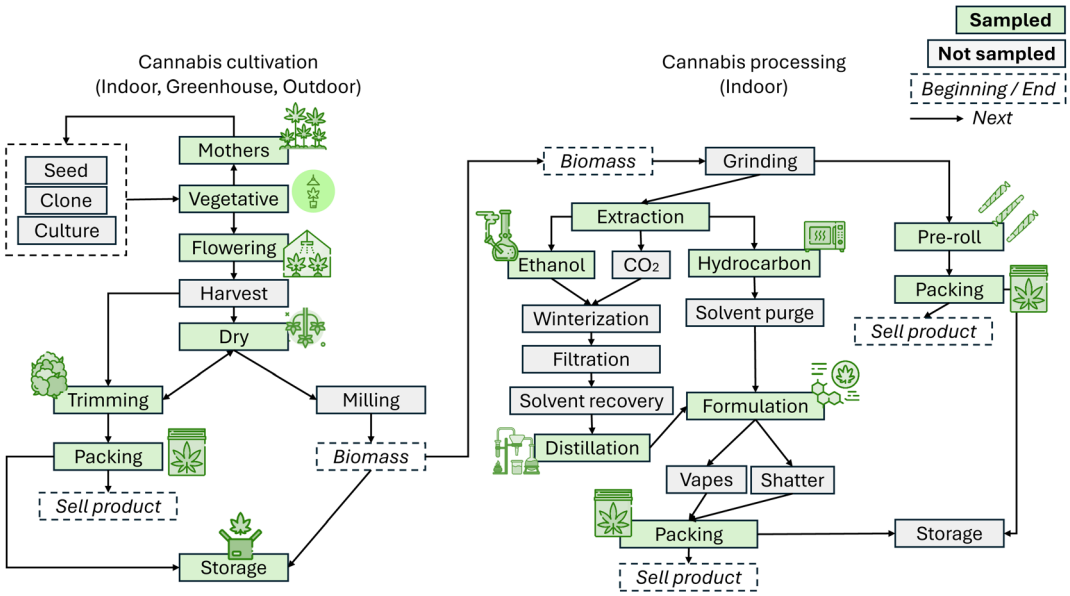

Fig. 1 A flowchart of the cannabis life-cycle demonstrates the connections between cannabis cultivation and cannabis processing. The processes are colour coded by the stages sampled in this study - green ones represent stages sampled. In the case of extraction, of the three main ways applied in the industry, only carbon dioxide (CO_2) method was not sampled. Grey color boxes represent stages/processes not sampled. The arrows indicate the typical transition between stages/processes in each industry. Beginning and terminal stages/processes are highlighted with dashed contour.

introduction), trimming (in this facility performed by machine), packing, and storage. We were not able to sample the harvesting activity because we were not allowed to have our instruments present during the process and during milling because the process had to be rescheduled (Fig. 1).

The CPF is an approximately 1400 m^2 cannabis processing and extraction facility with average annual shipment volumes of 1500 kg of cannabis products (defined as "standard processing", may possess >2400 kg of dried cannabis each calendar year[57]). Products include pre-rolls, dried flower, vapes, concentrates and other extraction products. We were able to sample in the pre-roll room (performed by a machine in this facility), packing room, ethanol extraction room (where tetrahydrocannabinolic acid, THCA, and cannabidiolic acid, CDBA, are separated from plant material), distillation room (where crude oil is further refined to isolate the desired cannabinoids), formulation room (where the product flavor is boosted), and hydro extraction room (also known as purging in vacuum ovens) process rooms. We were not able to sample the grinding, winterization (subjecting crude extract mixed with alcohol to freezing temperatures), filtration, solvent recovery (extracting target products from waste or by-product solvents), and storage rooms either due to space availability, or because the room was not in use at time of measurement (Fig. 1).

A detailed description of rooms and operational conditions in each facility, including HVAC schedule, lighting, floor area, space volume, number of plants and/or processing dry weight is available in the Tables S1–S5 of the ESI†.

2.4 Instrument operation

Terpenes were measured *via* Gas Chromatography coupled with Flame Ionization Detection (GC-FID), using the GC-FID 8610C and Peak Simple software (v4.90) by SRI Instruments. The column used for terpene separation was a 30 m × 0.53 mm I.D. 1.0U MXT-502.2 capillary column (diphenyl/dimethyl polysiloxane phase, range: −20 °C to 320 °C), which is a low-polarity stationary phase and a good match for hydrocarbons such as terpenes.[58] The temperature program consisted of: hold at 40 °C for 1 min, then ramp at 10 °C min^{-1} until reaching 280 °C, similar to the one used by Wang *et al.*[8,10] and finally hold at 280 °C for 5 min in order to bake-out any leftovers (30 min total). The only event triggered at the start of the program was zeroing the FID signal (usually 15 mV to 35 mV before each run). The helium carrier gas (He, 99.9999%, Linde Canada Inc.) was set at 11 psi (20 ml min^{-1}) and the hydrogen (H_2, 99.9999%, Linde Canada Inc.) used to light the FID flame was set at 20 psi (25 ml min^{-1}). A further Thermo Scientific™Click-On™Inline Gas Filter was used to prevent moisture and oxygen intrusion into the carrier gas. The air necessary for the FID flame was set at 5 psi (250 ml min^{-1}). The flame ignite setting was −752 mV and the temperature of the FID detector in high gain was set at 300 °C to avoid water and eluted peak condensation.[59]

2.5 Calibration

Calibration occurred prior to sampling using two standards solutions from RESTEK, which together comprise 22 terpenes (Table 1). From each original standard (2500 μg ml^{-1}), five diluted solutions were prepared, resulting in calibration concentrations of 1000 μg ml^{-1}, 100 μg ml^{-1}, 10 μg ml^{-1}, 1 μg ml^{-1}, 0.1 μg ml^{-1}. These concentrations were used to build the calibration curve so that we could characterize environments with low terpene concentrations (*e.g.*, vegetative room) and high concentrations (*e.g.*, trimming)[14] without the need to recalibrate or use different settings.

Table 1 Terpenes sampled in this study. Limit of detection was calculated using repeated samples of 10 μg ml^{-1}. Calibration chromatograms are found at Fig. S14 and S16

Terpenes	Formula	Limit of detection (LoD)[a]	Retention[b] (min)
Cannabis terpenes standard #1, 2500 μg mL^{-1}, isopropanol, 1 mL per ampul			
α-Pinene	$C_{10}H_{16}$	1.76	6.07
Camphene	$C_{10}H_{16}$	1.93	6.47
β-Pinene	$C_{10}H_{16}$	2.30	7.09
β-Myrcene	$C_{10}H_{16}$	2.58	7.33
δ-3-Carene	$C_{10}H_{16}$	2.54	7.69
α-Terpinene	$C_{10}H_{16}$	2.66	7.87
(+/−)-Limonene	$C_{10}H_{16}$	3.67	8.09
p-Cymene	$C_{10}H_{14}$	3.78	8.23
Ocimene	$C_{10}H_{16}$	3.02	8.48
γ-Terpinene	$C_{10}H_{16}$	3.56	8.74
Terpinolene	$C_{10}H_{16}$	4.84	9.31
Linalool	$C_{10}H_{18}O$	1.94	9.60
(−)-Isopulegol	$C_{10}H_{18}O$	2.19	10.56
Geraniol	$C_{10}H_{18}O$	1.57	12.10
β-Caryophyllene	$C_{15}H_{24}$	3.32	14.75
α-Humulene	$C_{15}H_{24}$	3.01	15.30
cis-Nerolidol	$C_{15}H_{26}O$	4.06	16.34
trans-Nerolidol	$C_{15}H_{26}O$	4.96	16.78
(−)-Guaiol	$C_{15}H_{26}O$	3.60	17.47
(−)-α-Bisabolol	$C_{15}H_{26}O$	3.38	18.58
Cannabis terpenes standard #2, 2500 μg mL^{-1}, isopropanol, 1 mL per ampul			
1,8-Cineole	$C_{10}H_{18}O$	1.48	8.56
(−)-Caryophyllene oxide	$C_{15}H_{24}O$	1.56	17.78

[a] Area under the peak converted to μg ml^{-1}. [b] Average of five samples.

Each injection of 1 μl was made by depositing the sample in the column to avoid boiling point discrimination. The 10 μl syringe used was then washed in acetone three times, dried, and washed one time in isopropanol prior to each loading. Polynomial fit calibration curves had R^2 values between 0.879—0.999 (Fig. S14†). Blanks (*i.e.*, only carrier gas) were run in between each dilution injection showing no contamination (Fig. S16†). We noticed that for the last two solutions of 1 μg ml^{-1} and 0.1 μg ml^{-1} the terpene FID signal was undistinguishable from noise. Thus, using repeated samplings of the 10 μg ml^{-1} and the equations described in Armbruster and Pry[60] we estimated the Limit of Detection (LoD) for each terpene (Table 1).

2.6 Sampling protocol

For the operation of the GC-FID we used a combination of procedures.[61–63] First, the MTX 502.2 column was baked at 300 °C for six hours one week prior to sampling in each facility. We also cleaned the instrument in between rooms using lint free wipes (Kimwipes®) and isopropanol (70%) to avoid transferring terpenes between rooms and other sources of contamination.

The indoor air sampling routine consisted of moving the GC-FID to the selected room, installing the gas connections, and applying the Quality Assurance (QA) and Quality Control (QC) procedures. Those consisted of performing H_2 and He leak checks before every sampling. Additionally, we turned on the carrier filter bake-out switch twice, and treated the column at 150 °C for 10 min while baking occurred. Next, the calibration program was loaded, and the oven was returned to 40 °C. Then, up to four column blanks (*i.e.*, only carrier gas) were performed prior to sampling start.

The GC-FID generally sampled between 10 am and 10 am of the following day to capture the workday hours and the overnight profile (*i.e.*, no person or activity performed). Some rooms had restricted operation hours that had to be followed. For instance, grow rooms needed all lights off, including those of our instruments, between 11 am and 11 pm, meaning that any instrument handling had to be performed outside those hours and the screen of the computer and other equipment had to be covered in between, so as to not disturb the plants' night-time metabolism.

Due to the unique challenge of sampling continuously in an uncontrolled environment with restricted access, the protocol adopted was a mix of established procedures such as U.S. EPA Methods TO-15 and TO-17,[64,65] NIOSH 1552 (ref. 66) and recent GC-FID autonomous approaches.[67]

The protocol started with terpenes sampled through PFA (Perfluoroalkoxy) 1/8″ tubing[68,69] of length ≈ 150 cm at a flow rate of 120 ml min^{-1} and trapped in a Tenax®TA cartridge[70–72] for either one min or 11 min. The trapping time reflected the expected concentration of the room. Essentially, in rooms where the concentrations were expected to be high (*e.g.*, drying and trimming), the one min protocol was adopted to avoid saturating the column. The entry port was set at 155 °C to avoid water condensation, and the FID detector was set at 300 °C.

One minute before the trapping ended, the Tenax®TA trap began heating from 35 °C to 200 °C. After trapping concluded, the valve switched from the load to inject position, releasing

terpenes into the column. The calibration temperature cycle began immediately after the valve switch, starting at 40 °C. Once the cycle was complete, the valve returned to the load position, and the trap was baked by heating from 200 °C to 250 °C over two minutes, while the vacuum pump removed any residual contents.

After baking, the system cooled to 40 °C, the FID signal was zeroed, and the cycle repeated without sampling the indoor air, ensuring a field blank (*i.e.*, carrier gas) is associated with each sample. The PeakSimple v4.90 software automated these steps, initiating a new run every 15 minutes. Fig. S18† provides an overview of the protocol.

2.7 Post processing and analysis

A series of Python scripts were developed to semi-automate the analysis of the 277 sampling chromatograms we collected. They function by (a) assisting the creation of a log file, (b) adjusting peaks based on fluctuations in the retention time, (c) aggregating multiple samples per room into one spreadsheet (d) exporting multiple chromatograms as .pdfs. Additionally, further Python scripts were developed to generate times series, box-plots, and heat maps of samples. All scripts can be downloaded from Scripts. Chromatograms for each sample are available in Portable Document Format (.pdf) in this repository: Samples. We converted the area under the peak to concentration using eqn (1).

$$C_{\text{ppb}} = I \times V_{\text{cal.inj.}} \times \frac{1}{\text{MW}} \times \frac{1}{F \cdot t} \times \frac{1}{4.09 \times 10^{-5}} \quad (1)$$

In eqn (1), C_{ppb} is the concentration in parts per billion (ppb); I is the standard equivalent concentration in nanograms per microliter (ng μl^{-1}); $V_{\text{cal.inj.}}$ is the volume of standard used during calibration (μl); MW is the molecular weight of the chemical in grams per mole (g mol^{-1}); F is the flow rate in milliliters per minute (ml min^{-1}); t denotes the trapping time in minutes (min); and 4.09×10^{-5} is an aggregated conversion factor (see full equation on Section S1.6†).

2.8 Emissions estimation

2.8.1 Calculations. Because we aim to understand the change in terpene emissions within each stage of the cannabis plant life-cycle, in this study we report the emissions of each room individually (*e.g.*, Samburova *et al.*[7]), rather than the overall facility-level emissions (*e.g.*, Urso *et al.*[16]), using eqn (2)–(9) similar to Urso *et al.*[13].

The CPF had a noticeable cannabis smell within its fenceline, and the CCF is surrounded by vegetation and farms, thus we assumed a conservative outdoor BVOC concentration of 1% of the facility's mean value $\bar{C}_{\text{BVOC}_{\text{facility}}}$, which is in-line with other studies[7] and terpene odor thresholds.[18]

$$F_{\text{room}_{\text{in}}} = 0.01 \bar{C}_{\text{BVOC}_{\text{facility}}} \times \text{AER}_{\text{room}} \times V_{\text{room}} \quad (2)$$

where $F_{\text{room}_{\text{in}}}$ is the mass flow rate into the room, in kg h^{-1}; AER_{room} is the air exchange rate, in h^{-1}, and V_{room} is the room volume, in m^3;

The information about the type of HVAC system, including schedule and extraction capacity, were provided by both facilities (Tables S1–S5†). We were not able to measure the actual Air Exchange Rates (AER) of the rooms, but the values calculated (10–40 h^{-1}) using each indoor environment dimensions (V_{room}) and HVAC capacity (Q_{ext}) match facility averages in the literature.[3]

$$\text{AER}_{\text{room}} = Q_{\text{ext}} \times 1/V_{\text{room}} \quad (3)$$

Loss due to dry deposition (L) was assumed to occur only at indoor environment walls and floor, for simplicity. Thevenet *et al.*[73] quantified the deposition of (+/–)-limonene onto several different surfaces for concentration ranges of 50 ppb to 900 ppb at 23 °C and RH 50% ± 2% - similar conditions as those within the CCF and CPF rooms. Although a partitioning coefficient of $\approx K = 0.08\text{–}0.19m$ was found for painted surfaces, about 50% was reversible (*i.e.*, emitted back). Using the room total area, terpene concentration, $K = 0.135m$ and reversibility of 50%, the total removal by dry deposition was estimated to range from 5–11% depending on the room. This value was then accounted for when estimating the removal by chemical reaction (R).

$$L_{\text{room}} = C_{\text{BVOC}_{\text{room}}} \times A_{\text{room}} \times K \times f \quad (4)$$

where L_{room} denotes the loss due to dry deposition, in kg h^{-1}; $C_{\text{BVOC}_{\text{room}}}$ is the biogenic VOC concentration in kg m^{-3}; A_{room} is the room surface area, in m^2; K is the walls surface partitioning coefficient, in (μmol m^{-2})/(μmol m^{-3}) and f is the reversible fraction between 0 and 1 (*e.g.*, 0.5 equals 50%).

We also considered terpene losses due to chemical reactions with O_3 and OH. We used direct measurements of O_3, nitrogen monoxide (NO), and nitrogen dioxide (NO_2) from a low-cost sensor co-deployed with the GC-FID (Section S1.7†) and indirect OH determination using eqn (6). Both facilities have no exposure to sunlight (*i.e.*, all light sources are from indoor lamps). We also measured the light spectrum in each room using the OCEAN FLAME Mini-Spectrometer (Section S1.7†) and observed no meaningful contribution in the 300 nm to 400 nm wavelengths that could result in O_3 or nitrous acid (HONO) photolysis and OH formation. Thus, we assume that the OH found indoors would be a function of outdoor OH and the balance between OH produced by terpenes reacting with O_3 and consumption by OH reacting with NO_2 and NO. The rate constants and OH yields used are found in the[74] and Section S1.8.†

$$R_{\text{room}} = k_{\text{OH}} C_{\text{OH}_{\text{room}}} C'_{\text{BVOC}_{\text{room}}} V_{\text{room}} + k_{\text{O}_3} C_{\text{O}_{3_{\text{room}}}} C'_{\text{BVOC}_{\text{room}}} V_{\text{room}} \quad (5)$$

in eqn (5), R_{room} represents the loss due to chemistry, in kg h^{-1};k_{OH} is the second-order rate constant for the reaction of hydroxyl radical (OH) with BVOC, in m^3 kg^{-1} h^{-1}; k_{O_3} is the second-order rate constant for the reaction of O_3 with BVOC, in m^3 kg^{-1} h^{-1}; $C_{\text{OH}_{\text{room}}}$ represents the hydroxyl radical concentration, in kg m^{-3}; $C_{\text{O}_{3_{\text{room}}}}$ is the ozone concentration, in kg m^{-3}; and $C'_{\text{BVOC}_{\text{room}}}$ is the BVOC concentration after accounting for the dry deposition, in kg m^{-3}.

$$C_{\mathrm{OH_{room}}} = C_{\mathrm{OH_{outdoor}}} + \frac{\sum k_{\mathrm{O_3+terpenes}}[\mathrm{terpenes}][\mathrm{O_3}]\phi_{\mathrm{OH}}}{(k_{\mathrm{OH+NO_2}}[\mathrm{NO_2}] + k_{\mathrm{OH+NO}}[\mathrm{NO}])} \quad (6)$$

in eqn (6), $k_{\mathrm{O_3+terpenes}}$ represents the rate constants for the reactions between ozone and terpenes (molecule^{-1} cm^3 s^{-1}); [terpenes] is the concentration of terpenes after accounting for dry deposition (molecules cm^{-1}); [O_3] is the rooms' ozone concentration (molecules cm^{-1}); ϕ_{OH} is the OH yield (fraction); $k_{\mathrm{OH+NO_2}}$ is the rate constant for the reaction between OH and NO_2, assumed to be 3.01×10^{-11} (molecule^{-1} cm^3 s^{-1})[75]; [NO_2] is the rooms' concentration of NO_2 (molecules cm^{-1}); $k_{\mathrm{OH+NO}}$ is the rate constant for the reaction between OH and NO, assumed to be 1.01×10^{-11} (molecule^{-1} cm^3 s^{-1});[75] and [NO] is the rooms' concentration of NO (molecules cm^{-1}). $C_{\mathrm{OH_{door}}}$ is the outdoor OH concentration, assumed to be 2.6×10^5 molecules cm^{-3} at nighttime (8 pm to 5 am) and 1.9×10^6 molecules cm^{-3} at daytime (5 am to 8 pm).[76] We decided to use Emmerson and Carslaw[76] results because they refer to measurements done in a hot summer at a location away (≥40 km) from a major urban center, relatively near (≤4 km) of a major road, in a site surrounded by agricultural land, thus matching in many aspects our facilities location. Furthermore, the values correspond to the concentration range reported in other field investigations made in British Columbia[77] and modeling studies for Canada.[78]

Only the CCF had a terpene removal control strategy in place inside the rooms (charcoal filters), rather than in the ventilation path. We assume that the concentration measured corresponds to the equilibrium concentration between plants emission, room ventilation, and control technology, thus the value for removal by treatment (C_{room}) can be also set to zero.

$$F_{\mathrm{room_{out}}} - F_{\mathrm{room_{in}}} = ER_{\mathrm{room}} - L_{\mathrm{room}} - C_{\mathrm{room}} - R_{\mathrm{oom}} \quad (7)$$

$$ER_{\mathrm{room}} = F_{\mathrm{room_{out}}} - F_{\mathrm{room_{in}}} + R_{\mathrm{room}} + L_{\mathrm{room}}(C_{\mathrm{room}} = 0) \quad (8)$$

$$F_{\mathrm{room_{out}}} = C''_{\mathrm{BVOC_{room}}} \times \mathrm{AER_{room}} \times V_{\mathrm{room}} \quad (9)$$

where, $F_{\mathrm{room_{out}}}$ is the mass flow rate out of the room, in kg h^{-1}; $\mathrm{ER_{room}}$ is the emission rate, in kg h^{-1}; and $C''_{\mathrm{BVOC_{room}}}$ the concentration after dry deposition and chemistry removal in kg m^{-3}.

2.8.2 Room-specific emission factors. For the CCF, we obtained the number of plants present in the vegetative, mother, grow (early and late development), and drying rooms. For the CCF trimming, Vault (storage), and packing rooms, and all the CPF rooms, we obtained the kilograms of cannabis material processed. We use this data to estimate the emission factors through eqn (10). Note that we were not able to measure the concentrations in the CCF without the charcoal filters inside the room. Furthermore, both the CCF and CPF do not have a VOC removal system in the path between room exhaust and stack emission. Thus, the emission reduction variable 'RE' was considered 0 for all rooms.

$$E = A \times \mathrm{EF} \times \left(1 - \frac{\mathrm{RE}}{100}\right) \quad (10)$$

in eqn (10), E represents the emissions in kg h^{-1}; A is the activity rate; EF is the emission factor; and RE is the overall emission reduction efficiency in percent (assumed to be 0 in this context).

2.8.3 2-D Pearson-emission analysis. After obtaining the temporal profile of terpene emissions in each room, we explored the relationship between each individual terpene and the total BVOC content using the Pearson correlation coefficient. Furthermore, we evaluated their correlation and their normalized emissions (eqn (11)) using scatter plots. In this work, we used a threshold of 5% of contribution to the total BVOC and Pearson correlation above 0.75 to categorize a terpene as 'Key contributor'. The full analysis can be found in the ESI.†

$$\mathrm{Norm(TERP}_i) = \frac{\mathrm{median(TERP}_i)}{\mathrm{median(total_{BVOC})}} \quad \text{for } i = 1, 2, \ldots, n \quad (11)$$

in eqn (11), Median(TERP$_i$) denotes the statistical median of the individual terpene emissions; Median(total$_{\mathrm{BVOC}}$) denotes the statistical median of the total terpene emissions; n is the total number of terpenes considered. Norm(TERP$_i$) is the vector of normalized emission values for the i-th terpene across all samples.

2.9 Screening dispersion modeling

We conducted screening dispersion modeling to investigate if the short-lived spikes observed in terpene emissions would lead ambient concentrations exceeding odor thresholds and thus detection by nearby communities. We used as input for the dispersion model the cumulative emission rates across rooms for the minimum, average, and maximum emission of β-myrcene, a compound routinely used as a marker of cannabis operations[10,11] and which has one of the lowest terpene odor thresholds (13 ppb),[18] and (+/−)-Limonene for comparison, since it was the key terpene in cannabis processing.

In this screening analysis, we assume that all rooms contribute to the facility output and there are no controls (*i.e.*, losses) between the ventilation that connects the rooms and the stack exit. We refer to this as a screening dispersion model because conducting a full dispersion analysis is outside the scope of this study and many more variables, such as building dimensions, terrain, land use, and local meteorology, would be needed. Instead, we use eqn (12) considering moderately stable (Pasquill–Gifford class F), neutral (Pasquill–Gifford class D), and moderately unstable (Pasquill–Gifford class B) atmospheric conditions.[79] The full suite of input variables are provided in the Section S1.9 of the ESI† and are either assumed (*e.g.*, 1.5 m for the receptor height and 5 m s^{-1} for stack gas exit velocity) or based on the facilities informed heights (4 m and 16 m) and typical wind speeds at the location obtained from the closest meteorological station (2–20 m s^{-1}). A sensitivity analysis varying the input variables was also conducted, and in total 7560 dispersion scenarios were investigated. After generating the dispersion model, we compare the concentrations in each scenario at several receptor distances to the β-myrcene and (+/−)-Limonene odor thresholds, 13 ppb (or 72.84 μg m^{-3}) and 38 ppb (or 212.91 μg m^{-3}), respectively.[18,80]

$$C(x,y,z) = \frac{Q}{U_s}\frac{1}{2\pi\sigma_x\sigma_y}\exp\left(-\frac{y^2}{2\sigma_y{}^2}\right)E(z) \quad (12)$$

$$E(z) = \left[\exp\left(-\frac{(z+H_s)^2}{2\sigma_z{}^2}\right) + \exp\left(-\frac{(z-H_s)^2}{2\sigma_z{}^2}\right)\right] \quad (13)$$

in eqn (12) and (13), C is the concentration ($\mu g\,m^{-3}$); Q is the emission rate ($g\,s^{-1}$); U_s is the stack height wind speed ($m\,s^{-1}$); σ_y is the lateral dispersion parameter (m); σ_z is the vertical dispersion parameter (m); y is the crosswind distance (m); z is the elevation of the receiver (m); and H_s is the effective stack height, calculated as $h_s + \Delta H$.

3 Results

To study the malodor BVOC time profiles of the cannabis sector we measured concentrations of 22 terpenes for eight rooms of

Table 2 Summary of terpenes total concentration and emissions across rooms and facilities

	# of samples	Concentration (ppb) (mean + − std. err.)	Emissions (kg h^{-1}) (mean + − std. err.)	Observations (a '%' is relative to the average)
Cultivation	183	$(2.57 \pm 0.24) \times 10^3$	—	—
Packing	16	$(6.21 \pm 0.18) \times 10^2$	$(2.39 \pm 0.07) \times 10^{-2}$	Emissions increase 17% during packing
Drying	41	$(3.80 \pm 0.05) \times 10^3$	$(1.45 \pm 0.02) \times 10^{-1}$	Steady emissions (±5%) unless door is open
Drying (no plants)	10	$(1.73 \pm 0.02) \times 10^2$	$(7.28 \pm 0.09) \times 10^{-3}$	1800% lower emissions than when in use
Grow (1 week propagation)	15	$(4.66 \pm 0.26) \times 10^1$	$(3.59 \pm 0.20) \times 10^{-3}$	Emissions increase 47% with the lights ON
Grow (1 week propagation + pest control[a])	11	$(2.85 \pm 0.60) \times 10^2$	$(2.16 \pm 0.46) \times 10^{-2}$	Emissions increase 585% when treated with pest control[a]
Grow (mature plants)	13	$(2.24 \pm 0.20) \times 10^3$	$(8.56 \pm 0.76) \times 10^{-2}$	Emissions increase 81% with the lights ON
Mother	15	$(1.37 \pm 0.50) \times 10^2$	$(1.32 \pm 0.04) \times 10^{-2}$	Emissions increase 19% with the lights ON
Trimming	27	$(8.00 \pm 0.88) \times 10^3$	$(3.09 \pm 0.34) \times 10^{-1}$	Emissions increase 87% during trimming
Storage (Vault)	16	$(3.03 \pm 0.08) \times 10^3$	$(1.16 \pm 0.03) \times 10^{-1}$	Steady emissions (±8%) (unless door is open)
Vegetative	13	$(5.00 \pm 0.86) \times 10^1$	$(4.94 \pm 0.82) \times 10^{-3}$	Emissions increase 163% with the lights ON
	6	$(7.76 \pm 0.95) \times 10^1$	$(7.39 \pm 0.90) \times 10^{-3}$	Emissions increase 37% with the lights ON
	# of samples	Concentration (ppb) (mean + − std. err.)	Emissions (kg h^{-1}) (mean + − std. err.)	Observations (a '%' is relative to the average)
Processing & Extraction	94	$(4.66 \pm 0.66) \times 10^2$	—	—
Packing area	15	$(5.67 \pm 1.12) \times 10^2$	$(3.01 \pm 0.59) \times 10^{-2}$	Higher emissions during work hours (6am–6pm)
Distillation	13	$(2.22 \pm 0.51) \times 10^2$	$(3.89 \pm 0.93) \times 10^{-3}$	Clear diurnal (6am–6pm) emission profile
Ethanol extraction	12	$(3.25 \pm 1.78) \times 10^2$	$(3.46 \pm 2.64) \times 10^{-3}$	Peak in emissions during extraction
Formulation	27	$(3.41 \pm 1.02) \times 10^2$	$(1.05 \pm 0.29) \times 10^{-3}$	Adding terpenes to the mixture increase emissions by 630%
Hydro extraction	15	$(1.31 \pm 0.14) \times 10^2$	$(8.68 \pm 0.87) \times 10^{-3}$	Peak in emissions during room preparation for extraction
Pre-roll	12	$(1.41 \pm 0.27) \times 10^3$	$(1.22 \pm 0.23) \times 10^{-3}$	Emissions increase 114% when machine is in use
Grand total	277	—	—	—

[a] Milk powder and hydrogen peroxide at low concentrations.

Table 3 Emission factors for each room sampled in the CCF and CPF

Cultivation	Description (kg h^{-1}) per [factor]	Emission factor (total terpenes) Min	Mean	Max
Vegetative	Plant cultivated	1.96×10^{-7}	3.08×10^{-7}	5.84×10^{-7}
Mother	Plant cultivated[a]	1.72×10^{-5}	2.20×10^{-5}	2.56×10^{-5}
Grow (1 week propagation)	Plant cultivated	4.30×10^{-6}	5.99×10^{-6}	8.82×10^{-6}
Grow (1 week propagation)	Plant cultivated with pesticides[b]	8.74×10^{-6}	3.61×10^{-5}	6.33×10^{-5}
Grow (mature plants)	Plant cultivated	2.16×10^{-4}	2.85×10^{-4}	5.32×10^{-4}
Drying	Plant hung dry	1.20×10^{-4}	1.45×10^{-4}	1.66×10^{-4}
Trimming	kilogram trimmed with machine	1.81×10^{-3}	6.18×10^{-3}	1.19×10^{-2}
Storage (Vault)	kilogram of product stored	4.15×10^{-5}	5.81×10^{-5}	6.27×10^{-5}
Packing	kilogram of product packed	9.02×10^{-5}	1.19×10^{-4}	1.41×10^{-4}
Processing & Extraction	**Description (kg h^{-1}) per [factor]**	**Emission factor (total terpenes) Min**	**Mean**	**Max**
Packing area	Package in discrete units[c]	1.17×10^{-6}	3.76×10^{-6}	1.09×10^{-5}
Distillation	kilogram of bulk extract	2.14×10^{-5}	7.77×10^{-5}	1.94×10^{-4}
Ethanol extraction	kilogram of mixture of biomass and extract	1.68×10^{-6}	2.30×10^{-5}	2.16×10^{-4}
Formulation	kilogram of bulk extract with terpenes added	2.73×10^{-5}	1.05×10^{-4}	8.13×10^{-4}
Hydro extraction	kilogram of bulk biomass	1.25×10^{-4}	1.93×10^{-4}	3.51×10^{-4}
Pre-roll	0.5 g or 1.0 g rolled unit	3.52×10^{-7}	9.77×10^{-7}	2.01×10^{-6}

[a] Observing the ratio of 5 vegetative to 1 mother plant. [b] Milk powder and hydrogen peroxide at low concentrations. [c] The net weight of dried cannabis that is intended to be consumed by means of inhalation in each discrete unit of a cannabis product must not exceed 1.0 g (Canada's Cannabis Regulations, SOR/2018-144).

the indoor cannabis cultivation facility (CCF) and six rooms of the processing and extraction facility (Facility P & E). Emissions were then linked to time patterns and rooms' environment conditions (Table 2). Emission factors were also calculated to improve current and future inventories (Table 3).

3.1 Terpene profile from cannabis cultivation

We explored the concentration timeseries of individual terpenes in order to answer the question if a speciated temporal profile of cannabis cultivation emissions is required from inventories. In the CCF, β-myrcene mean concentration varied between 25 ppb to 3200 ppb, and accounted for 39-78% of the total terpene, making it the dominant terpene across rooms. (+/–)-Limonene varied from 12 pbb to 3075 ppb, and accounted for 17-53% of the total terpene, making it the second most dominant. All other 20 terpenes accounted for less than 5% during practically all samples. Thus, the key terpenes that must be accounted in cannabis cultivation emissions profile are β-myrcene and (+/–)-Limonene.

Next, we investigated the link of total terpene concentrations and room activity. Concentrations varied across different rooms, with stability observed in storage areas and significant fluctuations in cultivation and processing spaces. The drying and Vault (storage) rooms had steady concentrations (*i.e.*, less than 10% variation across all samples) due to the limited staff activity during sampling. The plants' emission capacity is evident in the drying room, where $a \approx 1800\%$ increase in concentration was observed after the introduction of plants (Fig. 2). Conversely, the rooms with live plants and those with some processing activities such as trimming or packing had fluctuations throughout the day (Section S2.2).†

For the vegetative, grow, and mother rooms sampled, the action of turning the lights ON and OFF had a significant enhancement effect ($\approx$20%–90%) on terpene concentrations (*e.g.*, Fig. 3). Studies support that light spectrum, strain metabolism, and plant positioning affect the production of cannabinoids and terpenoids.[81–86] For instance, Ahsan *et al.*[81] found that terpene production generally increases in cannabis plants when growing under blue (430 nm) and red light (600-700 nm). Furthermore, Reichel *et al.*[84] found that buds less exposed to light (*e.g.*, shaded by higher buds) experience a significant decrease (50–77%) in key terpene production, such as β-myrcene and (+/–)-limonene.

Our measurements show that independent of plant age (*i.e.*, newly propagated or close to harvesting), the lights ON condition was associated with an increase in concentration whereas the lights OFF was associated with a decay. The observed increase and decay rate was steeper at earlier stages of plant development, likely due to the differences in strain metabolism and the fact that more blue (420–500 nm), red (700–750 nm), and infra-red (750–900 nm) light is provided to the cannabis plants when newly propagated (see Section S1.8†). For instance, when the lights were OFF the terpene concentration decreased (during one sampling cycle of $\approx$1 h and 42 min) from 475 ppb to 161 ppb (or −66%) in the early growing stage for "Blue Dream" plants treated with pesticides. Whereas for mature "Girl

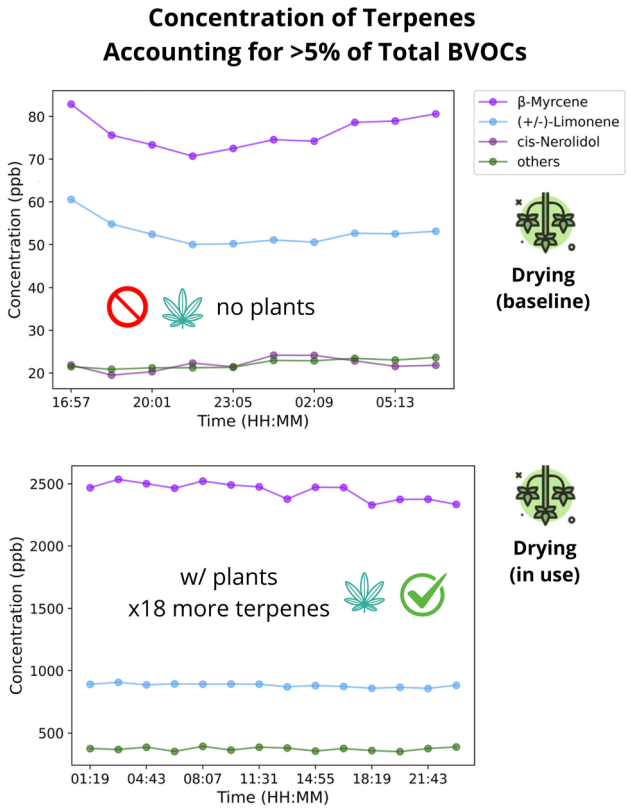

Fig. 2 Time series of terpene concentrations in the dry room before and after plant introduction (notice the different *y*-axis scales).

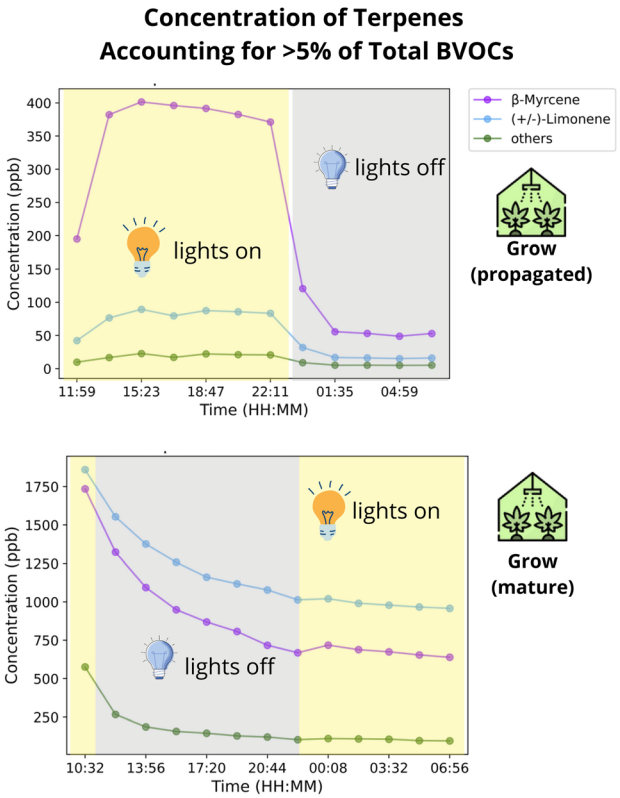

Fig. 3 The effect of lights ON on terpene concentrations (increase) during grow operation at different stages of plant life.

Scout Cookies" plants, the initial decrease during lights OFF was from 4170 ppb to 3142 ppb (or −24%). In the Grow rooms, We found similar terpene concentrations normalized both by number of plants and by weight as that of other studies(Table S10†).

At last, we compared our findings with the established literature in order to validate our method. We found the concentration per kilogram of plant (3.6–4.6 ppb kg^{-1}) in the Drying room to be in the lower-bound compared to other studies (3.2–13.2 ppb kg^{-1})[13] (Table S11†). In Urso *et al.*,[13] the lowest ratio of 3.2 ppb kg^{-1} was found for a drying room with the highest plant weight (1827 kg). Additionally, the door was open to a processing room, potentially increasing the total volume, changing the HVAC load, and decreasing concentration as opposed to having the door closed. In our study, the drying room had the door closed at all times, and also had a charcoal filter installed in the room, which contributed to lower concentrations. Furthermore, drying rooms sampled in Urso *et al.*[13] study had multiple strains present, while ours was only one, "Blue Dream".

For other rooms, the previously published studies consulted lacked production information (*e.g.*, number of plants, dry weight, cultivation area) or had diverging conditions (*e.g.*, strains in the room) for a fair comparison, however in terms of absolute concentrations, the Vegetative room of Urso *et al.*[13] (129.5 ppb) was within range of the CCF (27−136 ppb). The same could be said for the trimming operation: CCF (2326−15521 ppb) *vs.* Urso *et al.*[13] (4479−7763 ppb) and Silvey *et al.*[12] (6112−8090 ppb). Similar to previous studies,[7,9,13] we observed that as the life cycle of the plant progressed the emissions increased, starting at an average of 4.94 $\times 10^{-3}$ kg h^{-1} in the vegetative stage reaching a peak during the trimming activity, where we observed an average emission of terpenes of 3.09 $\times 10^{-1}$ kg h^{-1}.

3.2 Terpene profile from cannabis processing

Similar to the cultivation sector, we also explored the concentration timeseries of individual terpenes in the processing facility. In the CPF, (+/−)-Limonene mean concentration ranged between 60 ppb to 526 ppb, and accounted for 3452% of the total terpenes, thus being the dominant terpene across rooms. In second position was β-myrcene, with mean concentrations of 23 pbb to 470 ppb, or 15-33% of total terpene. Contrary to the CCF, though, was the fact that more terpenes contributed above 5% of the total concentration.

We followed up exploring the activity patterns influence in emissions. The time series of terpene concentrations had a clear diurnal pattern, with low concentrations between 6pm–6am and high concentrations between 6am–6pm (*e.g.*, Fig. 5). Additionally, emissions from the formulation, ethanol extraction, and pre-roll rooms were clearly correlated to room activity. In the formulation room, peak concentrations were associated with the activity of adding terpenes to the oil blend obtained during distillation, which resulted in concentrations ≈730% above the average (*e.g.*, Fig. 4). These peak emissions quickly dissipated within the GC-FID sampling interval (≈90 min).

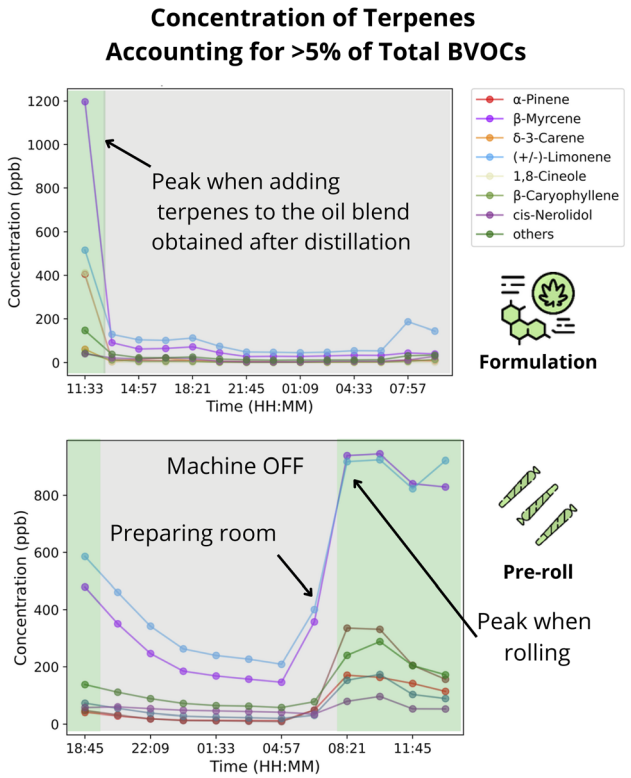

Fig. 4 Time series of the formulation and pre-roll activities, which caused spikes in concentration. In formulation, the peak is a result of adding terpenes to the vape mix being prepared. In the pre-roll, just by prepping the room bringing raw material inside cause an increase in concentration. When the pre-roll machine is in operation, concentration reaches a peak.

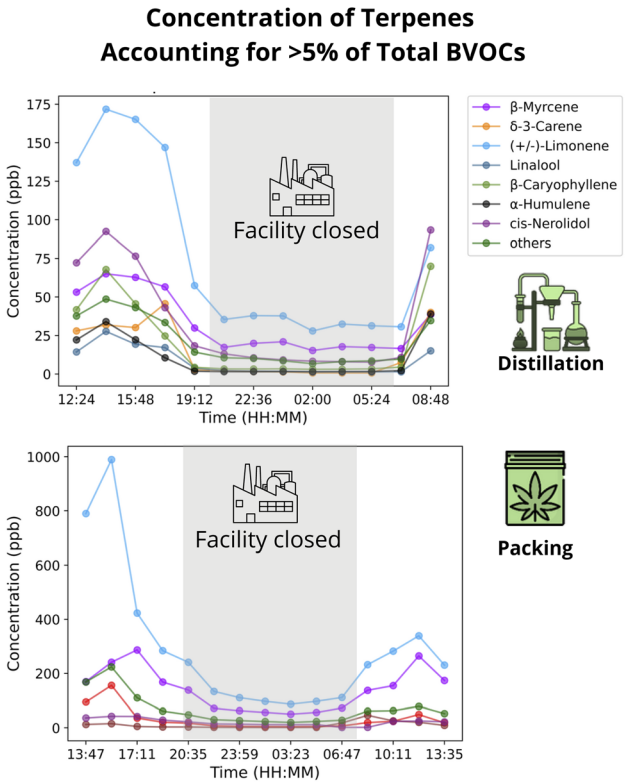

Fig. 5 Time series showing the reduction in terpene concentration in the distillation and packing rooms when the facility was closed and no work was performed.

As with the CCF, comparing the CPF emission factors, which are useful for building inventories, is challenging due to the lack of available production data for other published studies, such as dry weight processed or number of pre-rolls per batch. However, in terms of absolute concentration our results are comparable to previous work. For instance, in the CPF Pre-roll room (492–2919 ppb) *vs.* Silvey *et al.*[12] (1115–1980 ppb) and in the CPF Purge (*i.e.*, hydro extraction) room (84–250 ppb) *vs.* Samburova *et al.*[7] (180 ppb ± 20 ppb).

3.3 Timeseries variability of individual terpenes

In addition to the time variation of total terpene concentrations and emissions, we also assessed the time variation of individual terpenes, and how this variation correlated to total terpene emission variability (Section S2.3†). We observed that individual terpene time variation does not always follow the total terpene time variation.

For the cultivation facility, only β-myrcene and (+/−)-limonene, had a strong correlation ($r \geq 0.7$) with total terpene concentration for all rooms. The processing facility rooms had a minority of individual terpenes ($n = 9$), including β-myrcene, which were strongly correlated to total BVOC across all rooms.

Thus, not only is β-myrcene a candidate tracer of cannabis emissions, as highlighted previous studies,[10,11] but also the only terpene to have a strong linear relationship with total terpene concentration emitted. Another interpretation is that using a linear regression model to fit an averaged canister composition to a total terpene time series may misrepresent the actual chemical profile, since the majority of terpenes do not increase or decrease proportionally with total terpene concentration over time.

Apart from β-myrcene and (+/−)-Limonene, other terpenes that were notable (≥5%) contributors to total emissions included *p*-cymene, terpinolene, linalool, and *cis*-nerolidol, which alternate as the third and second most emitted in each life-cycle stage.

The joint analysis of correlation and emissions revealed that negatively correlated terpenes are either emitted in single bursts (*e.g.*, 1,8-cineole during trimming), or had higher concentrations in the room prior to an activity (*e.g.*, terpinolene in the trimming room). One hypothesis is that the emission of some species is only triggered by phenomena associated with minor total emissions, resulting in a lower profile in more emissive episodes. While it is well-known that terpenes emission is affected by biotic and abiotic factors,[82,87,88] to get a better comprehension of the triggers, we would have required a higher temporal resolution in our measurements of BVOCs.

We also found that although the overall emission time variation (in each room) is often more than ±100% for non-dominant terpenes, the absolute time variation is often ±0.1 kg h^{-1} in the CCF and CPF.

3.4 Relative removal rates are higher in the processing facilities compared to cultivation

Here we investigated the importance of each component of the mass-balance equation used to estimate emissions, and if they varied significantly between cultivation and processing rooms. Between removal rates due to chemistry (10^{-5} to 10^{-2} kg h^{-1}), terpene mass flow into the room (10^{-13} to 10^{-14} kg h^{-1}), and dry deposition (10^{-10} to 10^{-8} kg h^{-1}), (R) was more significant for the emission box model (Section S2.4†). The removal rates (R) at the CCF ranged from 5.69×10^{-5} kg h^{-1} to 4.58×10^{-2} kg h^{-1}, while at the CPF, R varied between 4.94×10^{-4} kg h^{-1} and 7.60×10^{-3} kg h^{-1}. These differences align with the higher terpene concentrations typically observed in cultivation rooms. However, the relative removal rate (R), defined as the ratio between emissions rates and removal, was significantly higher during processing and extraction operations than during cultivation (processing: 19.5–72.8% *vs.* cultivation: 1.7–13.9%). Overall, the total removal rates, along with those attributed solely to reactions with OH (R_{OH}) and O_3 (R_{O_3}), align with the estimations reported by Urso *et al.*[13].

3.5 Screening assessment of ambient air odor impacts considering time variation

For a terpene emission to be relevant in an odor community exposure assessment, the downwind concentration of that terpene must surpass the odor threshold.[21,89,90]

Our screening dispersion analysis indicates that out of the 7560 possible dispersion scenarios created for the CCF's average β-myrcene emissions of 0.373 kg h^{-1}, 88 (1.1%) may result in an episode of community-detectable odor event ≤500 m downwind.

Accounting for the increase in emissions during trimming (+0.132 kg h^{-1}), 241 (3.2%) combinations surpassed the β-myrcene odor threshold of 72.84 μg m^{-3}, including 18 under favorable atmospheric stability conditions (moderately unstable).

For the majority of the odor episodes, they occurred during stable atmospheric conditions, and at 2 m s^{-1} wind speeds measured at 10 meters height. The meteorological analysis (Section S1.10†) of the nearest station to the CCF suggested that such conditions occurred ≈18.2% of the hours during the year of sampling. Thus, although odor episodes are a small percentage of scenarios tested, they had the potential to occur almost 1/5 of the year.

For the CPF β-myrcene and (+/–)-Limonene emissions, as well as the (+/–)-limonene emissions of the CCF, no dispersion scenario resulted in concentrations above the odor threshold, suggesting that the combination of emissions above 0.4 kg h^{-1} and low terpene odor threshold (≤15 ppb) is needed to cause a community-detectable odor event from stack emissions.

4 Environmental implications

4.1 Key findings

This study shows that individual terpenes have a non-linear relationship with total terpene emissions in most cases. The composition of emissions during cultivation and processing is influenced by the room conditions, routine, and activity performed. Given the complexities in the emissions, we recommend future studies to carefully report on these parameters for more robust comparisons going forward.

For occupational exposure, the emissions variation may be of less importance, since, thus far, studies (included ours) have not shown total or individual terpene concentrations surpassing local exposure limits.[14] For community exposure (when emissions leave the facility's premises and interact with outdoor air), understanding the timing of increased emissions of compounds like β-myrcene is crucial, since this terpene have a low odor threshold, and is highly correlated to total emissions throughout the plant life-cycle, meaning that an environmental impact assessment could underestimate odor impacts if temporal variations in emission composition are not considered.

The temporal variation of β-myrcene (and (+/–)-Limonene) might also be important when considering each terpene's reactivity with atmospheric oxidants,[15] which can lead to the formation of ozone (O_3), ultrafine particles ($PM_{<0.1\mu m}$) in the form of secondary organic aerosols (SOA). Such knowledge might assist with sensitivity analysis of modeling studies (*e.g.*,[7,9,16]), helping explore the range of potential concentrations modeled at sensitive receptors and concentrations used in model validation.

Although driven by a few assumptions, our results support that only a small percentage (3.2%) of dispersion scenarios would lead to odor in a nearby community (≤500 m away). Nevertheless, the frequency of the meteorological conditions required to cause an impact during the sampling year was 18.2% of the hours. Therefore, future investigation concerned with this type of impact, as well as the need for odor control technology, should aim for evaluating facilities with an indoor cultivation capacity above 25 ton per year and exported products capacity above 1.5 ton per year, and be accompanied by meteorological analysis. Additionally, we only investigated stack emissions impact, which could differ from area and volume emissions from greenhouse and outdoor cultivation or those emissions in indoor facilities with a leakier building envelope or inappropriate outdoor waste disposal practices.

4.2 Study limitations

In our attempt to extrapolate terpene emission rates to multiple facilities, there remains the limitation that facilities have different operating conditions. For instance, our facilities were well-established and had some emission controls in place (Tables S2–S5†), which may not be the case for emerging or small facilities. While regulations are still at the early stages, some facilities are already adopting Best Environmental Practices (BEP) and Best Available Technologies (BAT) and others are not. Furthermore, each strain cultivated in a facility has its own odor potential. Therefore, each facility has its own potential impact depending on what is cultivated, meteorology near site, and receptor distance (*i.e.*, it is not just about size). Lastly, the industry is evolving according to the market needs and

strains cultivated/processed in one year might not be the same in the next. All these points must be taken into consideration when using our results.

Other limitations concern the scope of the samplings. For instance, many other VOCs such as butane[7] and *n*-Heptanal,[11] as well as Volatile Sulfur Compounds (VSC) such as 3- methyl-2-butene-1-thiol,[18–20] which can have odor thresholds much lower than β-myrcene, may undergo similar temporal variation of terpenes.

Accounting for variations in each terpene, VOC, and VSC, can significantly increase the complexity and cost of a study. For instance, incorporating non-terpene chemicals would necessitate purchasing more standards and potentially using multiple instruments. Space constraints in the rooms present another challenge, as accommodating many instruments may be impractical in some cases due to room layouts with limited free area.

Future work characterizing VOCs and other species with the same high time resolution as a Photo-Ionization Detectors (PIDs) detector (*i.e.*, real-time) could be achievable through PTR-ToF-MS[91–95] also coupled with GC.[96,97]

Another limitation of this study concerns the assumptions made during the mass balance calculations. Specifically, using the mean partitioning coefficient of (+/–)-limonene obtained from Thevenet *et al.*[73] for the deposition of all terpenes may not reflect true conditions, especially considering the range of chemical structures (*e.g.*, number of cyclic carbons, and the number of unsaturated bonds).[98] Similarly, we were not able to find information on the kinetic constants and yield for all terpene reactions with O_3 and OH (see Section S1.9†). Thus, we had to assume values between terpenes with similar chemical structure.

Lastly, a recent communication[99] outlined the development of a new trap for sampling indoors in cannabis facilities, and discussed the recovery efficiency of Tenax ®TA traps. We have not made corrections to the terpene values based on this communication, because both the analytical conditions (*i.e.*, thermal desorber parameters and gas chromatograph parameters) and experiments differ from our approach. For instance, Brown[99] sampled 10 L of air where we sampled 1.2 L maximum. We also performed multiple samples, baking the trap system between each sample. However, we wish to highlight Brown[99] here as it could be useful for future studies.

4.3 Study contributions

We present a replicable methodology for continuous terpene measurements in cannabis cultivation and processing facility rooms. This approach provides a more detailed characterization than PIDs or similar techniques which measure total VOCs (or BVOCs) or techniques relying on collecting limited, isolated samples over time using sorbent tube extraction for profiling.

The GC-FID approach also has less risk of loss or contamination during transport to and analysis in a laboratory, since the instruments stayed in the room where collection and analysis occur simultaneously. Through this method, we provide speciated and time-resolved emissions from each room sampled, covering most processes in the life-cycle of a cannabis plant, expanding the current literature database. This knowledge could assist in building emission inventories for the industry to support improved dispersion modeling of odorous emissions. The new GC-FID approach could also be incorporated to outdoor monitoring studies, which, currently, are very limited in number (*e.g.*, Wang *et al.*).[10]

Apart from the scientific contribution of our methods, the results of this work could be used as guidance for regulators towards improved emission inventory assessments in the cannabis industry. For instance, we demonstrated that individual terpene and total terpene emissions vary by a number of factors, with the key three being: light cycle, plants stage of life, and work and no-work hours. The emission factors we derived also add to the existing, but limited, information available, and address almost the full life cycle of cannabis. For industrial stakeholders, our results will assist in addressing odorous emission control. For instance, for a facility with the same capacity as the CCF, the use of more than one charcoal filter in the room would be required to avoid the peak in terpene concentration during trimming.

Data availability

Data for this article, including rooms terpene concentration and chromatograms, calibration and blanks chromatograms, and post-processing Python scripts are available at Zenodo at **https://zenodo.org/records/14606485** and **https://zenodo.org/records/14606488**.

Author contributions

Davi de Ferreyro Monticelli conceptualization, data curation, investigation, methodology, formal analysis, visualization, writing – original draft. Cynthia Pham investigation, writing – review & editing Sahil Bhandari methodology, writing – review & editing. Amanda Giang conceptualization, funding acquisition, project administration, supervision, writing – review & editing. Nadine Borduas-Dedekind methodology, resources, writing – review & editing. Naomi Zimmerman conceptualization, funding acquisition, project administration, supervision, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

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