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Critical Review

Cannabis Cultivation Facilities: A Review of Their Air Quality Impacts from the Occupational to Community Scale

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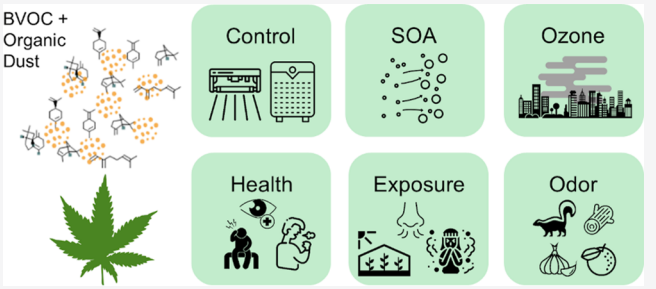
ABSTRACT: This review addresses knowledge gaps in cannabis cultivation facility (CCF) air emissions by synthesizing the peer-reviewed and gray literature. Focus areas include compounds emitted, air quality indoors and outdoors, odor assessment, and the potential health effects of emitted compounds. Studies suggest that β-myrcene is a tracer candidate for CCF biogenic volatile organic compounds (BVOCs). Furthermore, β-myrcene, D-limonene, terpinolene, and α-pinene are often reported in air samples collected in and around CCF facilities. The BVOC emission strength per dry weight of plant is higher than most conventional agriculture crops. Nevertheless, reported total CCF BVOC emissions are lower compared with VOCs from other industries. Common descriptors of odors coming from CCFs include "skunky", "herbal", and "pungent". However, there are few peer-reviewed studies addressing the odor impacts of CCFs outdoors. Atmospheric modeling has been limited to back trajectory models of tracers and ozone impact assessment. Health effects of CCFs are mostly related to odor annoyance or occupational hazards. We identify 16 opportunities for future studies, including an emissions database by strain and stage of life (growing cycle) and odor-related setback guidelines. Exploration and implementation of key suggestions presented in this work may help regulators and the industry reduce the environmental footprint of CCF facilities.



KEYWORDS: *Cannabis, Cultivation, Emissions, BVOC, Odor, Terpenes*

1. INTRODUCTION

The cannabis industry has rapidly transformed in recent years.[1] For example, as of November 2021, 19 states in the United States (US) have legalized cannabis for medical and recreational purposes.[2] In Canada, cannabis was federally legalized for recreational purposes in 2018, following legalization of medical cannabis in 2001.[3] Other countries such as South Africa, Mexico, and Uruguay also consider cannabis legal for medical and recreational purposes.[4] With more jurisdictions legalizing the consumption of cannabis for recreational purposes, the number of cannabis cultivation facilities (CCFs) has dramatically increased. In turn, environmental concerns over air emissions from CCFs have also grown, with emissions from CCFs recognized as contributors to regional odor.[5] Biogenic volatile organic compounds (BVOCs) emitted can also increase the formation of health-damaging pollutants such as ground-level ozone (O_3)[6,7] and particulate matter (PM).[8] These BVOC emissions also occur indoors at CCFs, which may represent an occupational hazard.[9,10] As a result, air quality regulators, public health agencies, and occupational health agencies have begun to explore options for curbing BVOC emissions at CCFs,[11−13] and the research community has identified an urgent need to characterize them.[14−16]

Cannabis sativa and *Cannabis indica* can be cultivated indoors, outdoors, or in greenhouses. When cultivated indoors or in greenhouses, ventilation systems and control equipment help maintain ideal conditions for plant growth. On the other hand, outdoor cultivation is more subject to the environment. The sequence of processes from cultivation to the final product is typically as follows: harvest, destemming, drying, grinding, decarboxylation, extraction, final processing, and packaging.[9] All of these processes may be carried out in the same facility, but it is not unusual to have one facility specialized in cultivation and another in processing. To date, some jurisdictions have required indoor, locked growing (e.g., Colorado, US[17]). However, this is another changing factor in the industry; for instance, the Colorado (US) government passed a bill in June 2021 that removed impediments to cannabis farming (outdoors), starting January 1, 2022.[18]

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The strength and composition of CCF emissions depend on numerous factors, such as plant stage-of-life,[6] strain,[19] and emissions control technologies.[20] Growing conditions (temperature, relative humidity, light)[21] and the indoor environment can also influence the emissions. Beyond this, little is known about the air quality impacts of CCF emissions due to a scarcity of published evidence and due to relevant information being dispersed across different academic fields (indoor air, outdoor air, odor assessment, health hazards) and gray literature. Therefore, there is a critical need for a review that synthesizes and analyzes current knowledge regarding CCF air emissions and that identifies knowledge gaps for future research.

This review aims to consolidate published information across all air quality assessment stages, from emissions to health impacts. It is divided into: the approach used during the literature search (Section 2), methods to assess air quality in and outside CCFs (Section 3), synthesis of findings on cannabis emissions and impacts from measurements and atmospheric modeling (Section 4), and the health effects at the receptors (Section 5). Lastly, Section 6 is a summary of findings and suggests future research directions, including areas of emphasis by stakeholder group. For definitions of the terms used throughout this review, refer to the Glossary.

2. REVIEW METHODS

Initially, a literature search was conducted in December 2020 in Web of Science using the keywords "cannabis cultivation" and ("emissions" or "odor"), which returned few results.[6,7,22] Likewise, "hemp cultivation" and ("emissions" or "odor") did not return studies of interest for this review. Given the difficulties encountered with the initial steps of a systematic review, the authors changed the approach. A second search was performed on Google Scholar using ("cannabis" or "cannabis cultivation") and ("voc" or "odor") as initial keywords. Studies were selected based on whether the abstract and title addressed 1) indoor or outdoor cultivation emissions, 2) monitoring or modeling of cannabis air quality impacts, 3) health effects at the occupational or community level, and 4) life cycle assessment of cannabis cultivation. Alerts were created and sent to the first author for every new article published throughout the process of writing this review (December 2020−November 2021). Subsequent studies or reports (e.g., guidelines) were found by scanning the reference list of initial studies and tracking citations of those studies. Reports from public agencies and project partners were requested to fill the gaps needed to perform synthesis and analysis. Lastly, Web sites, such as https://www.leafly.ca/,were consulted as valuable sources of strain types and cultivation strategies.

3. METHODS FOR ASSESSING AIR QUALITY OF CANNABIS CULTIVATION EMISSIONS

3.1. Gas Chromatography (GC) for Terpene and Cannabinoid Analysis. Reviews dedicated to cannabinoid and terpene characterization[23,24] identify GC coupled with a mass spectrometer (GC-MS) as the most common and preferred method to analyze cannabis content. However, this approach only detects nonacidic cannabinoids, because acidic cannabinoids undergo decarboxylation due to the high temperatures in the GC equipment.[24] Acidic cannabinoids can alternatively be measured by high-performance liquid chromatography (HPLC) which, if coupled with mass spectrometry (HPLC-MS), can differentiate overlapping peaks in the chromatograph.[25] Nevertheless, studies have demonstrated the power of GC by sampling plant material, usually using a headspace sample of parts of a cannabis plant, followed by GC-MS or GC coupled with a flame ionization detector (GC-FID). Headspace denotes the air above or surrounding the plant and can be sampled following a static or dynamic approach in either a laboratory or growing environment, using the whole plant or detached parts (see details in Tholl et al.[26]). Choice of sampling location can affect which VOCs are detected. For example, Hood et al.[27] sampled 5 mL of the headspace air containing VOCs emitted by 1 g of standard marijuana sample and detected the compound 2-methyl-2-heptene-6-one for the first time. Likewise, Rothschild et al.[28] sampled the headspace of a *C. sativa* plant upper part and found two pyrazines unique to the female plant. Wiebelhaus et al.[29] sampled the headspace of fresh leaves and flowers and determined that α-santalene, valencene, and β-bisabolene are unique to marijuana plants. Bueno et al.[30] showed through headspace GC-MS that the terpene content in inflorescences can be standardized by using airtight containers with external terpenes. Micalizzi et al.[24] reviewed the existing analytical techniques to characterize terpenes and cannabinoids of cannabis species. Most of the reviewed studies sampled inflorescences (hemp and cannabis grown for medical/recreational purposes) or derived products. A novel technique, GC-FID *fast*, was reported to detect terpenes and cannabinoids at the same time. Multiple studies have examined air samples (in contrast to plant material) and employed GC followed by some other method to explore occupational hazards, aroma profiles, and VOC emission profiles (Table 1).

There are techniques other than GC that can be used for analyzing cannabis emissions. For instance, Sherma and Rabel[34] considered the use of thin-layer chromatography (TLC) as a less expensive and labor intensive method to analyze cannabis inflorescence and suggest TLC as a complementary approach to GC-MS, GC-FID, and HPLC. At the other end of the spectrum, more expensive methods, such as proton transfer time-of-flight mass spectrometry (PTR-ToF-MS), have, to the best of our knowledge, not been applied to either indoor air of growing rooms or outdoor air sampling near CCFs. PTR-ToF-MS offers the advantage of high sensitivity (e.g., below 1 pptv sesquiterpene concentration in an urban environment), high mass resolution (6600 m/δm in V mode), and ultralow detection limits.[35] Furthermore, it can perform simultaneous measurements, which is ideal for reactive species such as terpenes.[36] For instance, Wang et al.[22] analyzed air samples near CCFs by GC-MS and GC-FID 1 to 7 days after collection and were not capable of identifying sesquiterpenes. In addition, they had to add 2 mL of an internal standard (decahydronaphthalene (DHN)) to GC samples to counterbalance potential losses in preparation (adsorption and desorption) and apply a treatment to distinguish coeluting peaks of D-limonene and β-phellandrene. In contrast, Li et al.[36] deployed PTR-ToF-MS for detection of terpenes in a forested area. Their results reported on the presence of diterpenes in the forest chemosphere and their diurnal cycle, together with monoterpenes and sesquiterpenes. In the urban environment, Han et al.[37] compared the performance of GC-MS and PTR-ToF-MS and highlighted the detection of oxygenated VOCs by the latter. The detection of additional compounds changed the relative observed VOC concentrations and their predicted ozone formation potential. In fact, the newly identified compounds such as methanol, acetic acid, propionic acid, and hydroxyacetone all had higher

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Table 1. Studies That Sampled Air from Cannabis Cultivation Facilities in Different Environments (Indoors, Outdoors, or Plant Enclosure) and Analyzed It Using Gas Chromatography

study	sample	method	goal	analysis	GC column (temp program)	key result
Couch et al.[9a]	indoor air of CCF (BVOC, fungal diversity)	evacuated canisters (packed: silica gel), personal and area samplers	explore occupational hazards	GC-MS-SIM	**dyacetyl**: 30 m × 0.32 mm i.d. capillary column, DB-5df = 0.25 μm (initial 100 °C, hold 1 min, program at 5 °C/min to 200 °C), **2,3-pentadione**: 60 m × 0.32 mm i.d. DB-1 capillary column, df = 5-μm (initial 60 °C, hold 4 min, program at 10 °C/min to 150 °C, hold 5 min, 20 °C/min to 200 °C)	detection of diacetyl and 2,3-pentanedione below occupational hazard
Knights[31]	indoor air of CCF (BVOC, odors)	air sampled in charcoal sorbent tubes	obtain aroma profile	GC-MS	performed by Analytical Chemistry, Inc., Tukwila, WA	terpenes concentrations: 50–160 ppb, major compounds: β-myrcene, limonene, β-pinene, α-pinene
Martyny et al.[32a]	indoor and outdoor air of grow rooms (fungal spores, terpenes, CO, CO_2, NOx)	personal sampler (Carbotrap 300 tubes), Q-Track, High Flow Personal sampler, 400-hole impactor, Air-O-Cell	explore occupational hazards	GC-MS	100% methyl silicone or 5% phenyl, 95% methyl silicone fused silica capillary columns of 0.25–0.53 mm I.D. (initial −50 °C, hold 2 min, program at 8 °C/min to 200 °C)	terpenes concentrations: at 50–100 ppb, major compounds: α-pinene, β-myrcene, β-pinene, limonene
Samburova et al.[6]	indoor air of CCF (BVOC, non-BVOC)	Teflon sampling tubes attached to medium-volume canisters (Tenax sorbent tubes)	obtain VOC profile	GC-MS and GC-FID	100% methyl silicone or 5% phenyl, 95% methyl silicone fused silica capillary columns of 0.25–0.53 mm I.D. (initial −50 °C, hold 2 min, program at 8 °C/min to 200 °C)	BVOC profile for the same facility is similar between rooms, except when comparing curing and growing
Silvey et al.[33a]	indoor air of CCF (BVOC, PM)	Dylos DC1100 Pro	explore occupational hazard	GC-MS	Stabilwax, 30 m, 0.53 mm ID, 3 μm film (35 to 135 °C at 10 °C/min)	terpene measurements typically below occupational hazard standards (20–100 ppm 8 h exposure)
Wang et al.[7]	plant enclosure (BVOC)	stainless steel adsorbent cartridges (Tenax TA and Carbograph 5TD)	obtain VOC profile	GC-MS and GC-FID	RESTEK Rtx-5 model 10224, 30 m, 0.32 mm ID, 0.25 μm film thickness (35 °C, hold for 1 min, 10 °C/min up to 260 °C)	detection of eucalyptol in samples, multiple strains and life cycle emissions investigated
Wang et al.[22]	ambient air near CCF (BVOC)	stainless steel adsorbent cartridges (Tenax TA and Carbograph 5TD)	obtain VOC profile	GC-MS and GC-FID	ESTEK Rtx-5 model 10 224, 30 m, 0.32 mm, ID, 0.25 μm film thickness (35 °C, hold for 1 min, 10 °C/min up to 260 °C)	distinguish β-myrcene as tracer compared to background

[a]These studies also performed surface swabbing for detection of cannabinoids and/or particle count, which are not relevant for Table 1 analysis but worth mentioning.

concentrations than toluene, the dominant compound previously identified via GC-MS.

Another technique, olfactometry analysis, is a powerful tool, complementary to GC-MS and GC-FID, to characterize the odor profile of cannabis emissions. It is conducted by human volunteers trained to perceive odors in a controlled environment. Olfactometry can be used to find odor concentration ($OU \cdot m^{-3}$), when the odor mix is analyzed alone, and Odor Activity Value (OAV), when assessments are coupled to GC. Rice and Koziel[38,39] sampled cannabis headspace and determined that VOCs with low concentrations but high odorous character (i.e., low odor thresholds) are mostly responsible for the odor. Even when GC-MS or other techniques are not available, olfactometry analysis can still be used to generate quantitative estimates of the odor concentration through the Odor Units (OU),[40] which quantifies the number of dilutions with fresh air necessary for 50% of a group of trained panelists to stop detecting the odor. When odor concentration ($OU \cdot m^{-3}$) is multiplied by the flow rate of emissions ($m^3\ s^{-1}$), the corresponding rate of odor emission in ($OU \cdot s^{-1}$) is useful for dispersion models and regulatory purposes.

3.2. Sampling Techniques. There are no guidelines specific to monitoring cannabis emissions. However, three guidelines have been previously established for measuring VOCs, BVOCs, and terpenes.[41−43] United States Environmental Protection Agency (US EPA)[41] Method TO-3 (device: cryotrap) and Methods 14A and 15 (device: specially-treated canister) are designed for nonpolar VOCs and highly volatile compounds, such as terpenes, sampled in ambient air. The US EPA[42] recommends auto-GC for hourly averaged measurements or three 8-h canister samples every third day. It also highlights the drawbacks of using Nafion dryers for monoterpene analysis, as they can interfere with compounds

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causing a loss of material. Lastly, NIOSH[43] Method 1552 recommends using a solid sorbent tube (coconut shell charcoal, 100 mg/50 mg) for terpene sampling indoors. As noted in Table 1, studies used different tubing content (Tenax TA, Carbotrap 300, charcoal, etc.) for sampling, and some sampling required modifications to the original method. Appendix 1 of the US EPA Compendium Method TO-17[44] provides a series of packaging material recommendations for sampling hydrocarbons, although specific recommendations for terpenes (or alkenes) are missing. A review of VOC sampling material[45] recommends Tenax TA, Unicarb, and Carboxen X for odorous VOCs and the use of chemically inactive material for terpene sampling. Based on the information reviewed, we suggest that more studies are required to compare the advantages and disadvantages of commonly used sampling techniques in cannabis research.

3.3. Odor Assessment. There are numerous research opportunities to examine cannabis odors and their impact using well established existing methodologies. Bax et al.[46] reviewed available categories of measurement techniques, including dynamic olfactometry, chemical analysis, GC-olfactometry, tracer analysis, instrumental odor monitoring by e-noses, field inspections, field olfactometry, and citizen science. Of them, only chemical analysis and citizen science have been applied to estimate the impacts of cannabis cultivation emissions. However, all of these methods can be applied to tracking the impact of odorous emissions from CCFs. Consider, for instance, dispersion models, which are widely applied to estimate odor annoyance and used as a part of the regulatory process in some countries.[47,48] These models can estimate a specific compound (tracer) concentration or the odor concentration in odor units ($OU \cdot m^{-3}$).[49] Modeling studies have focused on translating the hourly output of dispersion models to peaks of concentration each second or minute, which are more representative of odor events.[50−52] However, few studies have addressed the decay in odor perception with chemical reaction in the troposphere (e.g., Cartelle et al.[53]). In this sense, due to the reactivity of terpenes and their odorous nature, the modeling of CCF emissions presents a good opportunity to develop this concept. Conducting an odor assessment by utilizing an odor panel plusmodeling emissions combined with terpene chemical reaction downwind would help clarify the extent of terpene contribution to an odor episode. Measuring terpenes and their photooxidation products downwind would be required to validate the model results in such a study.

3.4. Other Techniques. Indoor air quality modeling can be useful for understanding the environment in which plants grow. Box models, for instance, are useful to indicate if the concentration of a pollutant could exceed legal standards with time. However, their assumptions of a steady-state and complete mix environment make them incapable of resolving concentrations throughout the domain. In this sense, Computational Fluid Dynamics (CFD) has been applied to indoor agriculture[54] and greenhouse growing for horticultural purposes[55] to optimize heating, ventilation, and air conditioning (HVAC) systems. CFD can provide spatially resolved temperature, relative humidity, and air flow data and can reduce costs and crop periods by helping to identify the optimal growing environment.[56] Using the CFD technique in cannabis grow environments has the potential to transform the industry.[57] CFD can also be used to evaluate the air quality indoors or in greenhouses and assess occupational health.[58] However, we did not find any studies that used CFD modeling to assess CCF air emissions. Furthermore, CFD combined with atmospheric chemistry could be used to simulate the concentrations other than terpenes, such as secondary particles, and other air pollutants inside the growing rooms. For instance, Sørensen and Weschler[58] applied CFD to study the concentration of D-limonene, α-terpinene, ozone, and their products in a room with air exchange rates varying from 0.5 to 2 per hour and found large concentrations gradients in steady-state conditions. However, CFD may require computational power not available in most facilities and thus may require industry−university partnerships.

A few studies have modeled secondary air pollutant formation from CCF emissions using chemical transport models.[7] Chemical transport models use reaction mechanisms (mostly derived from laboratory chamber experiments) to estimate concentrations of secondary pollutants formed via the reaction of primary pollutants in the atmosphere. The primary concern is the "lumped mechanism" applied in most models.[59] These mechanisms aggregate terpene species into a single surrogate compound named TERP, which is a major limitation given that previous research has shown different reaction rates and lifetimes of compounds emitted from CCFs in the atmosphere.[60] β-Myrcene, for instance, has a rate constant with OH 4× higher than TERP.[7] Explicit mechanisms, contrary to lumped ones, separate model species into individual compounds. Recent evidence suggests that the use of explicit mechanisms could produce different results. For instance, updating chemistry for terpenes and isoprene reactions in the MOZART chemical mechanism used in the Community Earth System Model/Community Atmosphere Model with full chemistry (CEMS/CAM-chem) reduced daily 8-h maximum average ozone bias by 7 ppb.[61] Another study showed that the model resolution of the inner grid (1 km vs 4 km) can affect the peak-ozone results by nearly ±50%.[62]

Inverse dispersion modeling can also be used to link the concentration of a particular compound to its source by estimating its back trajectory to the point of emission.[22,63] Knowledge of the air parcel passing through an industrial cluster allows for particular compounds to be targeted against background concentrations. Because most terpenes emitted by CCFs have a short lifetime in the troposphere, Wang et al.[22] modeled only 3 h prior to the observations. Wang et al.[22] used the HYSPLIT model,[64] but other models such as CALPUFF and TRAJ2D[53,65] are also viable options. While modeling air pollutant concentrations could be a cost-effective approach compared to monitoring, the lower spatial and/or temporal resolution of models and a lack of validation with ground-level monitoring data could lead to large errors. Using higher spatial and/or temporal resolution during the model run and experimental validation are both expected to improve the validity of modeling results. Moreover, while the chemical mechanisms used in models can determine the predicted downwind chemistry, an accurate estimate of the emissions is required for atmospheric chemistry impact assessments.

3.5. Key Gaps. From Section 3, four key gaps were identified. A synthesis of all key gaps is discussed further in Section 6. Based on this review, we suggest that future research focuses on the following:

1. Using more sensitive or rapid analysis techniques (e.g., GC-FID *fast* or PTR-ToF-MS) to identify terpenes and cannabinoids in air or plant samples.

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Environ. Sci. Technol. 2022, 56, 2880−2896

2. Modeling indoor air quality and other environmental variables (e.g., temperature, air flow) using tools such as CFD.
3. Modeling the air quality impacts of emissions in ambient air using a chemical method that treats the reaction of major terpenes emitted individually.
4. Conducting olfactometry analysis of emissions to establish odor emission factors. Identify drivers of odors and conduct odor impact assessment through modeling techniques and/or odor panels.

4. EMISSIONS FROM CANNABIS CULTIVATION

4.1. BVOC Emissions. Biogenic emissions from cannabis species vary in composition and strength based on the stage of plant growth.[19] However, emissions due to cultivation and processing (drying, sorting, trimming, and curing), which often occur at the same site, are poorly understood due to the limited number of facilities sampled. Here, we discuss results from studies that have explored BVOCs emitted by cannabis plants to infer the impacts of this emerging industry.

Wang et al.[22] compared the BVOC emissions from indoor facilities,[6] outdoor samples,[22] and samples from cannabis headspace,[19] and found that BVOC emissions vary in composition. Furthermore, the authors observed high concentrations of β-myrcene near CCFs but did not find high concentrations in other outdoor vegetated areas, suggesting that β-myrcene could be a sensitive tracer of CCF emissions. More research is needed to address how outdoor air quality is influenced by CCF emissions. Thus far, we know that the concentrations of monoterpenes near CCFs are at least four times higher than background,[22] but several times lower than concentrations indoors.[6] Samples taken indoors during the flowering stage (emissions peak) in four CCFs showed that the most abundant compounds were β-myrcene, D-limonene, terpinolene, α-pinene, and β-pinene.[6] However, the percentage of each emitted compound varied significantly between samples. For instance, β-myrcene ranged from 4% to 65% of the total BVOC composition.

Wang et al.[19] conducted leaf enclosure sample analysis of four (out of approximately 700 existing[66]) strains of cannabis species showing plant emissions on the 30th and 46th days of growth, corresponding to the vegetative stage and transition to the flowering stage, respectively. β-Myrcene was the dominant compound, present in all strains, in addition to eucalyptol and, to a lesser extent, D-limonene. Once again, the percentages varied significantly between samples. For example, β-myrcene ranged from 27% to 43% (30 day growth) and from 18% to 60% (46 day growth). Terpenes were also the most abundant chemical family in BVOC measured from hemp stems harvested after 15 weeks (end of flowering), accounting for 60% of total composition.[40] Other groups included alcohols at 17%, aldehydes at 13%, and ethers at 5%.[40] After 20 weeks (seed maturity), the emission strength reduced by half. Emissions of some compounds were found to increase with time, particularly those that provide defenses against bacteria, including β-caryophyllene, α-humulene, and δ,3-carene.[40]

Data from headspace measurements showed a very different BVOC profile than the plant oil measurements. Compounds such as α-pinene (55%), β-pinene (16%), myrcene (8.3%), and D-limonene (5.4%) dominated the BVOCs in headspace marijuana. They represented 85% of BVOCs, but were <10% of the plant oil,[27] mainly because the oil is composed of less volatile species, such as oxygenated terpenes and alcohols. The same compounds are the dominant BVOCs in the grow room sampled by Knights,[31] but the rank composition followed a different order: myrcene (68%), D-limonene (14%), α-pinene (13%), and β-pinene (5%). Due to the rarity of myrcene in cleaning and coating products, the author also proposed that it could be used as a sensitive tracer of cannabis operations, in agreement with Wang et al.[22] Furthermore, Knights[31] observed a steady increase in concentrations of all compounds from months 3 to 4 and an abnormal peak of myrcene in the seventh month, indicating emissions rates are different due to growth stages or for different strains. BVOCs collected and analyzed from male and female plants of two cannabis species during the flowering stage showed the most abundant compounds to be β-myrcene, (E)-β-ocimene, and terpinolene.[28] Two compounds are emitted uniquely by female plants: alkyl pyrazine and methoxypyrazine. A comparison of headspace VOC from marijuana, hemp, and other plants found the distinguishing compounds of marijuana to be α-santalene, valencene, and β-bisabolene. Conversely, compounds such as α-pinene, β-pinene, β-myrcene, β-caryophyllene, and α-caryophyllene were also found in nonmarijuana samples (21 plant species, including hemp).[29]

In general, it is difficult to establish an emissions inventory for CCFs given the substantial variability across plant strains, stage-of-life, and cultivation practices. For example, Wang et al.[7] aimed to model the impact of cannabis cultivation on ozone potential formation in Denver, Colorado, US. Due to the limited emissions inventory data, the authors assumed a single strain, plant life stage, and emissions capacity for all CCFs; one dry plant weight (750 g); a uniform number of plants per CCF; and constant growing conditions of temperature, relative humidity, CO_2 concentrations, and fertilizer use. They did not consider emissions from trimming, harvesting, and drying buds or the impacts of mechanical ventilation (i.e., all emissions assumed to vent to atmosphere). Sensitivity analyses were conducted to partially address these limitations, and the range of emissions was varied from 66 to 657 ton y^{-1}. A Canadian agency also compiled the emission strength from cannabis plants.[67] Emission factors have been reported by plant and by cultivation area, with average plant density (indoors cultivated) ranging from 1.9 to 4.3 plants m^{-2}. During the flowering stage (peak BVOC emissions), CCF BVOC emission factors ranged from 2.38 g d^{-1} $plant^{-1}$ to 744 mg d^{-1} $plant^{-1}$. Converting to the cultivation area indoors, emissions factors varied from 2.5 g d^{-1} m^{-2} to 5.12 g d^{-1} m^{-2}. Another way to report emission factors is by weight of dry plant. The vegetative state emission factors were estimated to range from 4.9 to 8.7 μg Cg^{-1} h^{-1}.[67] The same agency[11] compared the emissions factors per dry weight of cannabis (57 g kg^{-1} y^{-1}), Douglas fir (11 g kg^{-1} y^{-1}), and tomato (1.5 g kg^{-1} y^{-1}). Overall, by merging the cannabis emissions factors[7] and typical agricultural crops reported in the literature,[68] the BVOC emission factors (per dry weight of plant) from cannabis cultivation are higher (Figure 1).

We summarize the current knowledge of emissions and the composition profile of cannabis plants during their life cycle[69] (Figure 2). It is evident that there is variability in the composition of cannabis emissions. One study[70] suggested that the terpene profile among flowers of different strains could vary significantly. Allen et al.[70] tracked down the terpene synthase enzymes (enzymes that catalyze terpene formation) of 240 *C. sativa* cultivars to genetically map their terpene content. They isolated terpenoids from female plants, after drying and

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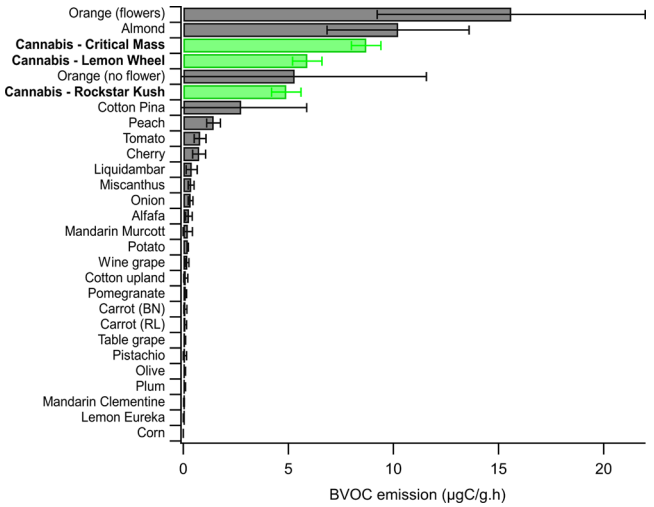

Figure 1. Comparison of emission factors from cannabis strains obtained in Samburova et al.[6] (green) and common crops obtained in Gentner et al.[68] (gray).

homogenizing their inflorescence for GC-MS analysis. This analysis ties to emissions because the nonoxygenated terpenes in the plant's inflorescence end up getting emitted during the flowering stage. Thus, knowing that the terpene composition may vary significantly from species to species implies that each CCF emission profile will be different. Their GC-MS results revealed α-pinene, β-pinene, β-myrcene, β-caryophyllene, D-limonene, and terpinolene were the major compounds in samples. Terpinolene appeared as a dominant compound in a minority of samples (14%), but was barely detected (<1% of composition) in the other 86% of samples. The other top five compounds were also present at low concentrations (or were not detected) in a few samples. Allen et al.[70] also explored the linear relationship between terpenes in cannabis flowers. Some were highly correlated (e.g., terpinolene and α-phellandrene, R^2 = 0.92). β-Myrcene, the compound most reported as a tracer of cannabis operation, had modest correlations with α-pinene ($R^2 \approx 0.4$) and β-pinene ($R^2 \approx 0.7$). Thus, it appears necessary to create a database of strains and emissions profile across the growth cycle. Exploring intraspecies correlation of emissions will improve regulation development, scientific understanding, and industry best practices for emissions reduction.

4.2. Odorous Emissions. Another important issue with CCF emissions is variability in odor production and the thresholds at which various compounds or mixtures of compounds may be perceived as offensive or annoying. Strunk[5] grouped cases in which annoyance due to odors from CCFs led to legal action. They found that people residing near CCFs reported nausea and eye irritation as symptoms caused by strong odors experienced on their properties. Odor descriptors associated with CCFs varied from the typical "skunky" to "citrus" or "balsamic".

An analysis of VOC concentrations during odor episodes may assist in odor source attribution. This type of odor assessment is challenging, however, because tracer compounds may not be the most important odorous agent. For instance, some studies showed that BVOC from cannabis samples also contained small amounts of alkyl pyrazine (0.84%) and methoxypyrazine (1.25%). These compounds have some of the lowest known odor thresholds (0.002 ppb).[28] Cannabis odor has also been associated with the presence of dimethylsulfide in trace amounts. Dimethylsulfide has a strong rotten egg smell with an odor threshold of 3 ppb.[39] Another study points to 3-methyl-2-butene-1-thiol as the cause of the "skunky" odor in cannabis.[71] When evaluated by the Odor Activity Value (OAV), other compounds such as nonanal and decanol can become tracers for the cannabis aroma.[39] They are present in lower concentrations but also have lower odor thresholds. Nonanal, for example, is expected to have a longer lifetime in the troposphere than most terpenes;[60,72] thus if a sufficient amount is emitted, it could cause a nuisance

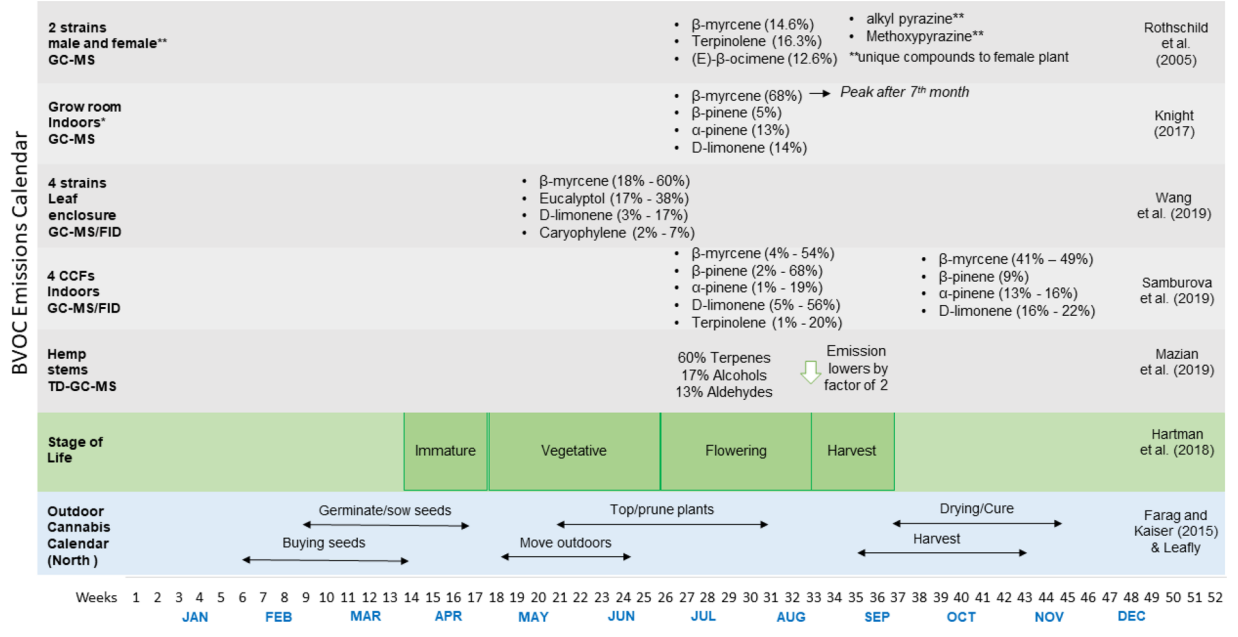

Figure 2. Life cycle of cannabis biogenic volatile organic compound emissions; values in brackets indicate the % in the sample. Studies that indicated the life stages of a plant were used to match the calendar year of outdoor cultivation. In indoor cultivation, this cycle can be shortened by controlling the environment, and all phases of the plant life cycle can happen in different rooms simultaneously.

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Environ. Sci. Technol. 2022, 56, 2880−2896

downwind of cultivation facilities. The odor description mainly associated with nonanal/decanol is "citrus" or "greasy", of which the former has been reported for cannabis smell.[73]

In hemp production, considerable odorous emissions occur during field retting, which refers to the practice of allowing the harvested hemp stems to decompose naturally on the field for several weeks. Mazian et al.[40] observed that the odor concentration and persistence were higher during the first weeks of retting when the stems had been harvested after flowering rather than at seed maturity. They reported "acceptability level" and "intensity" of odors arising from stem harvesting at each life stage based on a panel of six volunteers. The panel found the odors very unacceptable (−4.3 harvested at seed maturity and −4.9 after flowering on a 0 to −5 scale) and of average intensity (3.3 harvested at seed maturity and 3.5 after flowering on a 0 to 5 scale). "Dry/Green plants smell" were the descriptors most used, followed by "soft", "fermented", and "humus".[40]

In a study involving 52 volunteers,[73] of which only three had not smoked cannabis previously, participants were asked to assign a descriptor for 10 cannabis flower samples and provide an odor rating from 0 (not at all) to 10 (extremely). The three most cannabis-related descriptors were "pungent", "earthy", and "herbal". The three least cannabis-related were "butter", "menthol", and "coffee". The highest mean rating was 6 (pungent), and the lowest was ≈0.6 (coffee). No comparison of perception between cannabis users and nonusers was made.

To summarize our findings, we aggregated results from previous studies into Figure 3, which illustrates the terpenes that may contribute to the odor in cannabis samples at the vegetative stage,[19] flowering stage,[6,28,31] and drying/curing stage.[6] The most abundant terpene in all stages, β-myrcene, had an "earthy", "musky", and "fruity" smell. Other terpenes such as α-pinene and β-pinene smelled like "pine tree", limonene odor was characterized as "citrus", and eucalyptol smelled "minty".[74] However, we must stress that the odor tracers of cannabis emissions still require further investigation, especially looking beyond terpenes, as previous studies have shown other compounds of interest.[39] This gap should be addressed to improve control efficacy.

Only two studies have measured CCF odor impacts, one outdoors and the other indoors. Eltarkawe and Miller[75] demonstrate how sources can be attributed to odor events using social participation and knowledge of wind patterns. In their study in Denver, CO, the cannabis smell was associated with less than 4% of odor reports. Knights[31] quantified odorous emissions from a growing room in adjacent occupied spaces. They characterized volatile compounds and their associated odor thresholds experienced in the office and apartment immediately above the plantation area. They found β-myrcene (smell: earthy, musky) concentrations in the range 24 to 39 ppb across all sampled locations and held it as most likely responsible for the "strong" odor experienced by the office and apartment users due to its low odor threshold (13 ppb). However, other compounds such as nonanal and n-heptanal were also present, and the author indicated that they contributed to the odor experienced as much as β-myrcene.

Impacts from odorous emissions can also be investigated by inverse and forward dispersion modeling. In a conference proceeding, Maher et al.[63] used the HYSPLIT back trajectory model and citizen science to address the odorous impacts of CCFs and other industries in Metro Vancouver, Canada. They found that 23% of the reports in 20 weeks were related to CCFs.

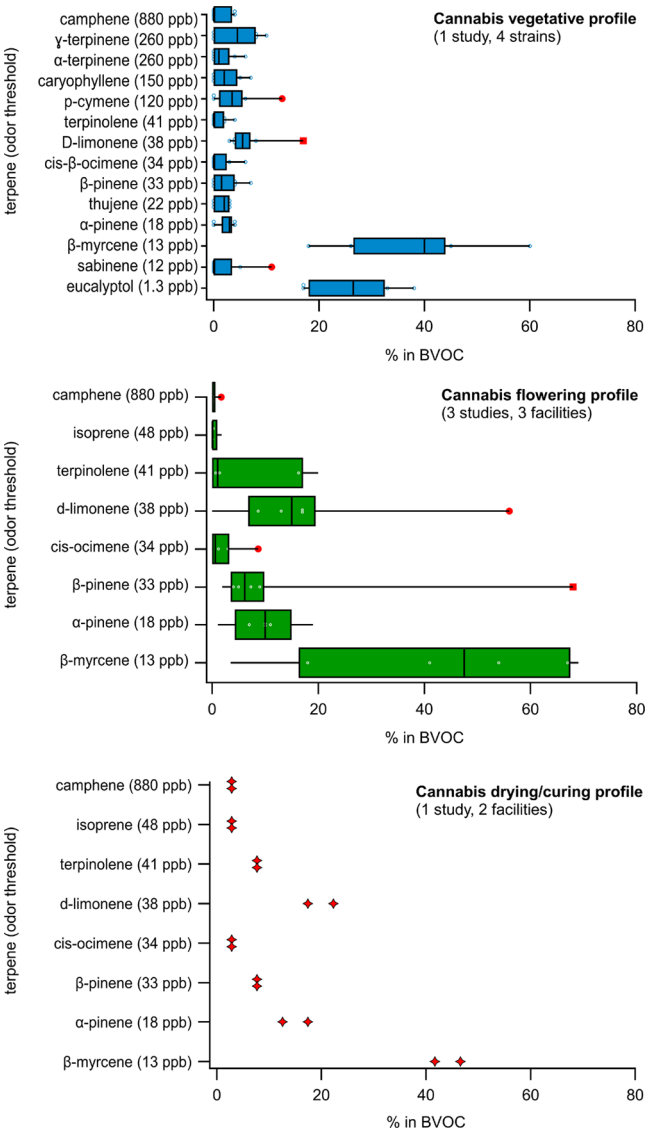

Figure 3. Terpenes possibly relevant to the cannabis odor during the flowering, vegetative, and drying/curing stages. % in BVOC indicates the terpene percentage in the total sampled BVOC.

No peer-reviewed study was found to use forward modeling to assess odor annoyance caused by CCF emissions, but the gray literature from consulting companies provides some insights.[76−78] For instance, in two studies,[76,77] the odor emissions in OU were different (809 OU/s vs 199 OU/s) for two CCFs with equal capacity (≈1700 plants), each using carbon filters. Furthermore, by comparing the OU/s of CCFs with other odor sources,[49] it is possible to demonstrate that the odor from a CCF with 1700 plants is equivalent to 10^{-3} ton s^{-1} of municipal solid waste processed, 0.06 m^3 s^{-1} of treated wastewater, or livestock operations with 30 pigs or 1600 chickens (Figure 4, with additional details in the Supporting Information). Nevertheless, in all agency reports, the impacts of CCF emissions were below odor concentrations limits.

4.3. Secondary Pollutant Formation. In addition to odor, emitted BVOCs can contribute to the formation of other secondary chemical species such as formic acid, mostly through reactions with hydroxyl radicals (OH), nitrate radicals (NO_3), or ozone (O_3).[60] For the major terpenes reported in studies thus far, the reactions with OH, NO_3, or O_3 occur in minutes to

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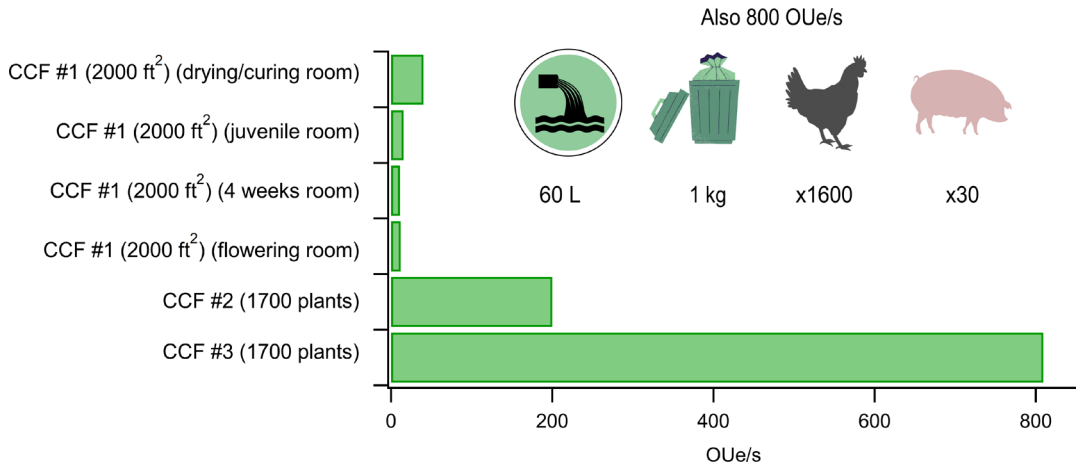

Figure 4. Emissions in $OU \cdot s^{-1}$ of different cannabis cultivation facilities and by room.

Table 2. Lifetime of Major Compounds Emitted by Cannabis Cultivation Facilities and Products of Their Reaction with Yield Higher than 0.1 in the Troposphere (Adapted from Atkinson and Arey[60])

terpene	+OH	(products)[a]	$+O_3$	(products)	$+NO_3$	(products)
β-myrcene	39 min	acetone, formaldehyde, $CH_2CHC(CH_2)CH_2CH_2CHO$	50 min	acetone, formaldehyde, $CH_2CHC(CH_2)CH_2CH_2CHO$, OH	6 min	(−)
β-pinene	1.8 h	nopinone, formaldehyde, acetone	1.1 day	nopinone, formaldehyde, OH, hydroxypine-ketones	27 min	organic nitrates, carbonyls
α-pinene	2.6 h	pinonaldehyde, acetone, formaldehyde, organic nitrates	4.6 h	pinonaldehyde, formaldehyde, OH	11 min	pinonaldehyde, organic nitrates, carbonyls
D-limonene	49 min	4-acetyl-1-methyl-cyclohexane, endolim	2 h	formaldehyde, formic acid, OH	5 min	endolim, organic nitrates
terpinolene	37 min	4-methyl-3-cyclohexen-1-one, acetone, formaldehyde, formic acid, $C_{10}O_2H_{16}$	13 min	4-methyl-3-cyclohexen-1-one, acetone, OH	0.7 min	(−)
β-caryophyllene	42 min	(−)	2 min	formaldehyde	3 min	(−)

[a]For α-pinene and β-pinene, 13 compounds are not shown due to yield less than 0.1.

days in the atmosphere (Table 2). Some of the products of these reactions are known to cause health effects. For instance, formaldehyde levels above 1 ppm ($\approx$1.25 mg m^{-3}) may cause eye irritation and nausea,[79] two symptoms that were previously reported for those living near CCFs.[5] However, concentrations above 1 ppm are rare because formaldehyde has a short life in the atmosphere (4 h to 1.2 days) and is readily photooxidized into CO_2 or reacts with OH to form formic acid.[60] Yet, formic acid exposure can cause the same health effects as formaldehyde exposure.[79]

Low-volatility products of terpene photooxidation may condense to form secondary organic aerosol[80] at the right conditions (e.g., temperature, UV light, relative humidity, NOx concentration), as shown in controlled laboratory studies.[81−87] Research in controlled outdoor environments[88−90] found that for vegetated areas, *cis*- and *trans*-pinonic acids were the two major compounds in sampled secondary particles, formed mainly through photooxidation of α-pinene. The particles formed (*cis*- and *trans*-pinonic acids) had diameters of 3−5 nm, and the mix was generally in the 20−40 nm size range.[88,89] Some compounds emitted by CCFs react slowly relative to other BVOC emissions. For instance, Koch et al.[91] showed that under similar initial conditions, sabinene, associated with oak forest emissions, reacts more quickly during ozonolyis than cannabis-related β-pinene, limonene, α-pinene, and terpinolene, and it has a higher secondary organic aerosol formation yield.

Little is known regarding the contribution of primary CCF emissions to indoor and outdoor concentrations of secondary PM downwind of a facility. It is understood that the major compounds emitted from CCFs react in the atmosphere to produce fine and ultrafine particles.[92] Attribution of air pollution to CCF facilities through source apportionment approaches requires the identification of tracer chemicals. As stated previously, the presence of β-myrcene may indicate the contributions of the CCF.[22] Also, photooxidation of β-myrcene does not appear to produce pinonic acid, which is a tracer secondary compound of BVOC oxidation from other vegetation.[88−90] However, photooxidation of β-myrcene does generate hydroxyacetone and terpenylic acid,[93] a difference that could be used for source apportionment (see the Supporting Information for details). Recent work suggests using secondary organic aerosol tracers improved the quality of source apportionment.[94]

Whether or not VOCs are biogenic, emission into VOC-limited regions can also contribute to the formation of ozone. In the troposphere, the NOx cycle is the only significant process that produces O_3 (through the breakdown by ultraviolet (UV) light).[92,95] In an atmosphere with low VOC concentrations, the available NO reacts first with organic peroxy (or HO_2) radicals, resulting in increased NO_2 and O_3 levels.[95] For instance, a study on the impact of CCFs in Denver, CO estimated that an increase of 1000 ton y^{-1} of BVOCs could increase daytime ozone concentrations by up to 1 ppb.[7] The Comprehensive Air

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Environ. Sci. Technol. 2022, 56, 2880−2896

Table 3. Best Available Control Technologies (BATs) for Air Emissions of Cannabis Cultivation, Adapted from Upland Agricultural Consulting[20d]

BAT	advantage	disadvantage	CAPEX[a] (OPEX)[b] (USD)	efficiency	lifespan	applicable to
carbon filters	simple to install, filter VOC, and odors	waste management required	$4,000 ($38,000)	50−98%	1.5−3 years	indoor, greenhouse
UV light	enhances carbon filtration by allowing reuse of carbon filters	high CAPEX	$98,000 ($5,000)	95%	1 year	indoor
biofilters	efficiently treat odors, simple to install, low maintenance	microbial agents need attention, pressure needed increases with time, adaptation time	$15,000 (N/A[c])	70−85%	3−10 years	indoor, greenhouse, outdoors
ozone generators	quickly oxidize VOC	ventilation required, ozone toxic to plants and humans, likely leads to PM formation	$3,800 (N/A[c])	40−60%	0.5−5 years	indoor, greenhouse
odor neutralizer	provokes reaction with terpenes and neutralizes odors	adds VOC to the air, added VOCs can form PM	$3,400 ($3,400)	20−90%	N/A[c]	indoor, greenhouse

[a]Capital expenditure (CAPEX) is given per acre of growing area (4,047 m^2). [b]Operating expense (OPEX) is given for 1 acre and a year period. [c]N/A = not available. [d]See the Supporting Information for the same analysis in a figure.

Quality Model with Extensions CAMx6.10 was used in estimations. An ambient monitoring approach has not been used to provide insights into secondary pollutant formation or ozone downwind. BVOCs also play a role in the formation of organic nitrates, which act as NOx reservoirs. Organic nitrates may then transport NOx elsewhere or be permanently removed from the atmosphere through deposition processes.[61]

4.4. Other Pollutants of Concern. Apart from BVOC emissions, carbon dioxide (CO_2) is a greenhouse gas and known driver of climate change, which is mainly emitted due to energy use from the cannabis production. Life cycle assessment[96,97] shows that for every dry kilogram of cannabis grown indoors, 2200 kg CO_2-eq to 6600 kg CO_2-eq is emitted to the atmosphere, a number that is strongly dependent on the source of the grid power. These emissions come mainly from lighting (33%), ventilation and dehumidification systems (27%), and air conditioning systems (19%) needed in indoor cultivation facilities.[97,98] Moving cannabis cultivation outdoors may greatly reduce carbon emissions from energy use, but it would increase water pumping, energy for the drying process, and vehicle use.[97] Mehboob et al.[99] developed complex models to simulate the energy consumption of CCFs. They identified lighting during the flowering stage as the most energy intensive activity.

4.5. Best Available Technologies (BATs) and Best Environmental Practices (BEPs) for Addressing Cannabis Emissions. To the best of our knowledge, there are only a few reports[11−13,20] that describe the Best Available Technologies (BATs) and Best Environmental Practices (BEPs) for managing air emissions from CCFs. Two factors influence the choice of the control technology: 1) cultivation type (outdoor, greenhouse, or indoors) and 2) scale of operation and/or capital and operational investment.[20] Here, we discuss the advantages and disadvantages of different BATs (Table 3).

We found that carbon filters are the preferred BATs for reducing odorous and VOC emissions indoors and at greenhouses.[13] They are composed of pellets of active charcoal that trap VOC via adsorption when contaminated air passes through the media, with the highest removal efficiencies achieved at low flow rates. However, high humidity levels negatively impact filter lifespan due to adsorption of water molecules that clog the filters, and high temperatures may cause desorption of trapped gases. Carbon filters are often coinstalled with UV irradiation, another control technology, which neutralizes odors by photocatalytic oxidation. Similar to carbon filters, biofilters use biological media (e.g., wood chips or bark mulch) to filter VOCs, and microorganisms embedded in the media metabolize VOCs to produce CO_2 and H_2O. The higher the contact time, the higher the efficiency. Biofilter performance can be enhanced by coinstallation with an ozone generator, which releases ozone to react with VOCs. The produced O_3 helps to unclog the biofilter in the case of biomass accumulation.[20] However, ozone generation favors the formation of ultrafine particles[100] in environments rich in VOCs, such as terpenes from CCFs. Finally, CCFs may also use odor neutralizers to reduce odorous emissions. These products, composed of natural gels and oils, react with terpenes in the air and chemically neutralize them. Odor neutralizers can be released passively from pots or vaporized from tubing or piping to create a curtain of neutralizing compounds around the perimeter of the CCF. Because they add chemicals to emissions, they are not an ideal solution, but the odor abatement efficiency can reach 90% depending on the product and contact time.[20] For particulate matter control, the use of High Efficiency Particle Arresting (HEPA) filters is recommended.[11] Thermal oxidation that utilizes heat to decompose VOCs is another option,[11] but was excluded from our review due to very limited information.

BEPs consist of measures that, together with control technologies, assist in reducing the impacts of CCF air emissions. Proper ventilation is critical, both to manage BVOCs[6] and growing conditions for the plants, as well as to mitigate odorous emissions and reduce energy costs. Two other examples are: (1) enclosing processing operations and (2) using enhanced barriers to block escape of indoor air (i.e., improving the building envelope).[13] Other measures, such as temporarily enclosing outdoor cultivation (for instance, at flowering), can also help mitigate odors.[11] Additional options include using an odor quantification instrument (e.g., a field olfactometer such as the Nasal Ranger) to actively manage odor mitigation activities[13] and timing harvests with periods of low ozone levels (e.g., fall and winter).

HVAC systems for CCFs must not only maintain high temperature and humidity levels, but also must be adaptable to different stages of the cannabis growth cycle. Many indoor facilities have a specific room for each stage of growth to avoid HVAC undersizing and oversizing as the requirements of the plants change.[21] CCFs may require up to 30 air changes per hour to maintain fresh air for plants.[97] High air exchange rates are important for plant growth because they prevent hot, humid air from being trapped in the facility, which can create an

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Environ. Sci. Technol. 2022, 56, 2880−2896

environment favorable to pests. In addition, high air exchange rates are useful for plant evapotranspiration.[21]

Aside from employing BATs and BEPs, having an air emissions management plan is critical. Recommended components include documenting emission controls (and their efficiency and maintenance) and monitoring odor events within and beyond the facility boundary. The air emissions management plan should also consider waste management, including odorous emissions, and control of temperature and humidity in the facility to maintain the efficiency of control equipment. Finally, although more studies are required, those determining where to site of CCFs could consider adopting a precautionary safe distance from sensitive receptors, such as hospitals, long-term care facilities, schools, and daycare centers. Some regulators suggest a distance of 200 m.[11] Calculations of optimal distance from sensitive receptors should consider the facility size (thus emission strength), control technologies installed, and meteorological conditions.

4.6. Key Gaps. From Section 4, five key gaps were identified. Based on this review, we suggest that future research focuses on the following:

1. Developing a database of cannabis terpenes emissions by strain and stage of cultivation cycle.
2. Identifying odorous compounds other than terpenes emitted by strains.
3. Measuring the formation of ozone and secondary particles downwind of cannabis cultivation facilities.
4. Developing guidelines for CCF siting that consider location of sensitive receptors, size of the facility, BVOC emissions, and odor exposure.
5. Conducting source apportionment studies linking terpenes or secondary particles in ambient air to cannabis cultivation facilities.

5. POTENTIAL HEALTH EFFECTS

5.1. Occupational Hazard. Reviews suggest that workers at CCFs are exposed to organic dust (molds, pollens, bacteria, other allergens, and bioaerosols), VOCs, fungicides, and pesticides.[10,101] While most prior investigations of occupational exposure have focused on hemp processing operations,[102−104] the cannabis industry has drawn more attention of late[9,32,33,105,106] due to legalization in some jurisdictions and distribution of products with higher cannabinoid content than hemp. Previous assessments of CCFs by the U.S. National Institute for Occupational Safety and Health (NIOSH) detected the presence of *Botrytis cinelea* (a.k.a "gray mold") in workers' breathing zone, which can trigger hypersensitivity pneumonitis.[10] The presence of endotoxins in air samples was higher during processing activities, such as grinding, although the reported levels were below occupational exposure limits[9] (see information about pollen in the Supporting Information).

As with endotoxins, particle mass concentration (PMC), particle number concentration (PNC), and terpene concentrations are elevated during manipulation tasks (e.g., trimming, sorting, prerolling, etc.). Silvey et al.[33] found mean PMC of 59 $\mu g\,m^{-3}$ and 50 $\mu g\,m^{-3}$ and PNC of 4.4×10^6 count m^{-3} and 4.3×10^6 count m^{-3} during trimming and prerolling operations, respectively, much higher than the office space sampled for comparison (19 $\mu g\,m^{-3}$ and 4.3×10^6 count m^{-3}). The same study also found terpene concentrations of 6400 and 3020 ppb during trimming and growing operations sampled for 8 days, respectively, three to seven times higher than the office sampling site (280 ppb). An interview of CCF workers found that 71% presented some work-related symptoms, and the majority of symptoms (65%) was respiratory.[106] Because the majority occupationally exposed study population was also active consumers of cannabis, the authors could not determine whether the occupational exposure to cannabis dust was the causal agent. However, what makes occupational exposure unique is that workers are mostly in contact with "raw" material, whereas consumers are exposed to processed or combusted material.[10] Raw material is often composed of larger particles (e.g., organic dust, allergens, impurities) that are filtered by airway defenses, while combusted material is composed of smaller particles and gases that are inhaled and penetrate deeper in the respiratory system.[10] Thus, a study conducted on workers that samples sufficient numbers of active consumers as well as workers that do not consume cannabis could provide further insights in occupational hazard exposure and health.

The literature reviewed here advances our knowledge of indoor air quality in CCFs; however, additional data are required to enable a fair comparison across them, including the following: indoor air quality management (ventilation, filtration, etc.), growing conditions (temperature, relative humidity, soil), life stage, and number of plants grown/processed. Of the three studies that provide such information, the type of facility (legal vs illegal), facility infrastructure, and/or the study purposes differ. For instance, Martyny et al.[32] investigate fungal spores, terpenes, and non-VOC pollutants (CO, CO_2, NO_x) in illegal cannabis growing facilities ranging from 11 to 670 plants. Samburova et al.[6] measured BVOC and nonbiogenic VOC in four licensed commercial cannabis CCFs ranging from 36 to 183 plants. While Martyny et al.[32] found terpene concentration ranging from 50 to 100 ppb in grow rooms, Samburova et al.[6] found concentrations of 21−290 ppb under typical conditions, and 1034 (±10) ppb when lights and fans were off. Silvey et al.[33] found high occupational exposure to airborne terpenes in the large indoor grow rooms (900 m^2 and 2700 m^2) of two cannabis facilities, with mean daily concentrations of 19 $mg\,m^{-3}$ (≈3500 ppb). Tasks such as trimming subjected workers to even higher exposures of 45 mg m^{-3} (≈8400 ppb). Lower exposures were found in the 10-h sampling conducted by Knights[31] (83 ppb), but no information on the size of the facility was reported. The European Commission[107] has provided tentative limits for indoor terpene concentrations, ranging from 40 to 400 ppb. Using these limits, both illegal and legal facilities were found to exceed the lowest standard and, without control technologies, the highest standard as well. However, when compared to individual terpene exposure guidelines[108] (e.g., 90 ppm for D-limonene short-term exposure), observed concentrations are far from exceeding the standard. Other pollutants such as CO_2, CO, dyacetyl, and 2,3-pentadione were mainly found below guideline values proposed by occupational health authorities.[109] Organic dust was an exception, where Fishwick et al.[102] found exposures ranging from 23 to 484 $mg\,m^{-3}$ in a 6-h shift.

5.2. Community Scale. Emissions from CCFs may affect public health at the community scale through exposures to: (1) high concentrations of terpene oxidation products, (2) high concentrations of particulate matter and ozone, and (3) odor.

A review of significant health effects[8] from terpene oxidation products (OPs) reported higher blink frequency (condition: 175 ppb limonene OPs, 20 min exposure) in humans. In exploratory research by Rohr et al.,[110] the exposure of mice to OPs of D-limonene and α-pinene, two compounds also emitted

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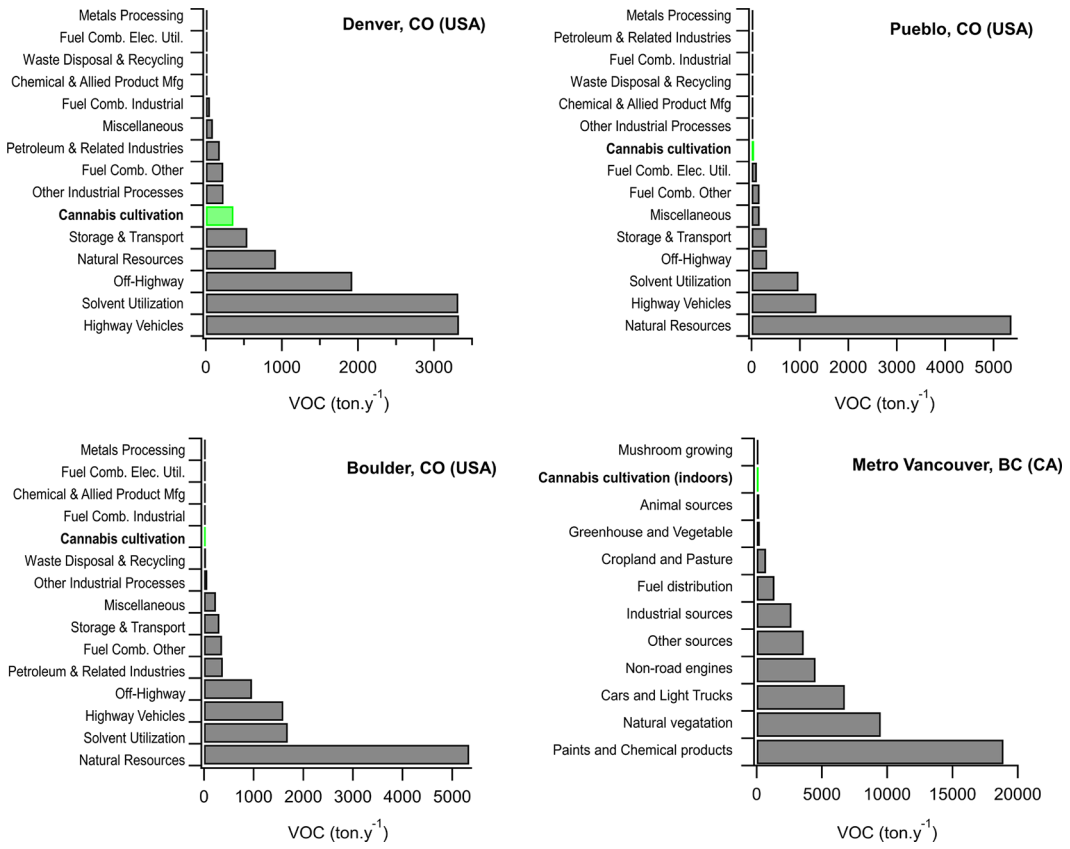

Figure 5. Comparison of emissions from cannabis cultivation facilities, assuming higher-end emissions in the Wang et al.[7] study and other sectors obtained via the US EPA.[137]

by CCFs, has been shown to cause upper and lower airway adverse effects during acute and long exposure. Effects from OPs derived from the limonene + ozone reaction were reversible within 6 h. However, there appears to be a higher risk (enhanced irritation) of exposure to OPs versus exposure to terpenes or ozone alone. A major limiting factor of Rohr et al.[110] is the high concentration used (≈50 ppm for terpenes). If a proper ventilation system exists or the OPs are diluted outdoors, these concentration levels are not expected.[6,31]

As mentioned in Section 4, adding VOCs in a VOC-limited region may favor the production of ozone. Regulation has been in place for years in many municipalities (e.g., Metro Vancouver[111]) to reduce these pollutants in air, and there is concern about any source that increases them. There is a large body of evidence on population health effects of ozone exposure.[112] Current studies[7] suggest that CCFs might already be changing the ozone concentration where they are located. The expected increase in size and number of facilities poses a challenge for regulators and potential risk for the population.

Apart from health effects due to increased concentrations of ozone, terpenes and their OPs, some health effects may be associated with odor. Odor events have consistently been linked to annoyance,[113−119] with specific reviews dedicated to evaluating techniques to measure this type of impact.[120,121] Psychological or mental stress has also been previously investigated,[122,123] as well as subjective well-being.[75] It is unusual to find studies that investigate physiological health effects, mainly due to the difficulty of separating the odor effect from the specific compounds, which is the tangible agent. However, studies point to a broad range of symptoms, such as burning eyes and throat, problems sleeping, nausea, and headache.[124,125]

5.3. Industry Guidelines. To date, we identified publicly available industry guidelines from the Colorado Department of Public Health and Environment,[126] California OSHA,[127] WorkSafe British Columbia,[128] and Ontario Workplace Safety and Prevention Services.[129] These guidelines compile health and safety plans for the industry, such as indication of use of personal protective equipment. However, some plans are still in development. There is also a special issue published in *Annals of Work Exposures and Health* dedicated to the cannabis industry.[130] These guidelines and recommendations should be reviewed as guidance material for existing and new CCFs.

5.4. Key Gaps. From Section 5, three key gaps were identified. Based on this review, we suggest that future research focuses on the following:

1. Conducting occupational hazard assessments that distinguish between users and nonusers.
2. Assessing toxicological impacts of exposure to terpene oxidation products and odorous compounds emitted from CCFs.
3. Developing an exposure standard for terpene emissions and oxidation products concentration in indoor facilities and ambient air near CCF.

6. SUMMARY OF FINDINGS

Cannabis cultivation is not a new industry;[1] however, with growing legalization for medical and nonmedical purposes in many jurisdictions, the contribution of this sector to atmospheric emissions is likely to increase. For instance,

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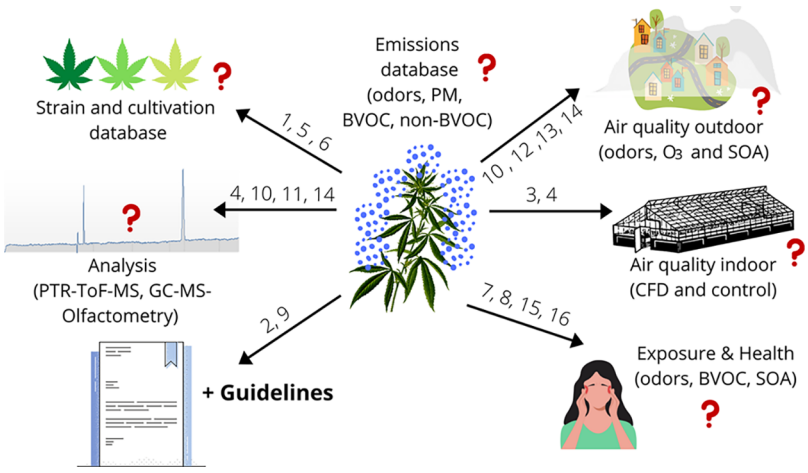

Figure 6. Current gaps in the literature regarding cannabis cultivation.

Canada first legalized cannabis for medical use in 2001 and, in 2018, was the first G7 nation to allow nonmedical (i.e., recreational) use and supply at the federal level.[3] With new legalization status, the number and size of facilities across Canada increased 8-fold,[131] and this trend could be followed worldwide.

Due to the emerging nature of the cannabis industry, its emissions compared with other sectors are considered small. Despite this, the cannabis industry is already a top-10 VOC source in cities where it has been legalized (see Figure 5). Analysis of limited data shows that CCF emissions are not as high as natural resources or transport-related sources. However, large uncertainties remain in CCF BVOC emission inventories (see Section 4). Additionally, source apportionment studies have thus far excluded BVOCs from CCFs. Recent investigations have highlighted the impacts of other new VOC sources in cities,[132] but have not considered the role of CCF emissions.

Regarding odorous emissions, only three studies were found in the literature that addressed annoyance at the community level. Strunk[5] found that nuisance legal actions (more than regulation) are posing a financial threat to the industry in the US, and Maher et al.[63] found that CCFs get more annoyance reports than wastewater treatment (another common odorous source) in Metro Vancouver. In contrast, Eltarkawe and Miller[75] found that "marijuana" has a small contribution to odor reports (4%) in Denver, CO, USA. In addition, although the characteristics of CCF odor have been investigated (see Section 4), the health impacts of these odors are unknown. Thus, there is a need for standard questionnaires or other methods to understand odor annoyance and health effects of people living in locations near facilities. One emerging approach is citizen science and mobile monitoring, which has already been applied in North America[133,134] and Europe.[135] It is also necessary to create an odor-related setback guideline for this industry, similar to what has been done for swine production systems.[136] This task could be achieved by distancing from communities or through odorous emission control. Another option is the adoption of nonexceeding thresholds at the property boundaries. This fenceline regulation approach could also prevent situations in which greenhouses previously established in residential neighborhoods for nonodorous crops are suddenly repurposed for cannabis varieties with potential for high odor.

While previous sections highlighted the potential air quality impacts of this industry, much still needs to be explored in order to better constrain uncertainties (see Figure 6). We provide a list of 16 fronts of action, organized by stakeholder group, that future research could address in order to increase our knowledge of the air quality impacts of cannabis cultivation.

6.1. Of Interest to Regulators. To understand the air quality impacts of an industry, it is first necessary to know its emissions. Cannabis cultivation emissions are still poorly understood, considering that we could identify emissions factors for fewer than 20 of 700+ species in this review. Furthermore, the existing emissions inventories and emission factors are still in development[138] and carry limitations. Thus, we recommend industry stakeholders/and or regulators (1) create a database of terpene and cannabinoid emissions of different cannabis strains under different growing conditions and life stages and (2) set guidelines for exposure to cannabis-related terpenes in the workplace and outdoors. This would also improve predictions from chemical transport models.

6.2. Of Interest to the Industry. Optimization of the product while still following laws and guidelines is a desired goal for any industry. As such, (3) CFD models paired with atmospheric chemistry applied to indoor/greenhouse CCFs could provide information on temperature, air flow, terpene emissions, and CO_2 concentration indoors. Such models could be run in collaboration with universities with a focus on healthier workplace environments and optimal facility design. Furthermore, previous studies showed that it is possible to control the terpene content of cropped inflorescence.[30] So, (4) developing novel techniques for terpene concentration and analysis or genetic modification could also increase the economic value of the crop and help standardize its terpene content and emissions.

6.3. Urgent Need for Odor Impact Assessment. Both monitoring and modeling assessment of odorous emissions from CCFs are lacking in the literature. Moreover, much of the available literature is focused on terpenes when previous research has shown that sulfurous compounds are also present in emissions[39,71] and can be very odorous.[120] Thus, (5) inventories of odorous emissions other than BVOC (e.g., aldehydes, dimethyl sulfide, and ammonia) and (6) olfactometry analyses of emissions at different life stages are needed. Another proposal is to (7) measure the odor impact using odor perception networks (odor panels) and (8) using electronic

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Environ. Sci. Technol. 2022, 56, 2880−2896

noses. In addition, (9) forward modeling of odorous emissions and evaluating the extent of the odor impact are required to establish safe distance from sensitive receptors.

6.4. Improving Atmospheric Chemistry Models. Understanding of formation of secondary organic particles downwind of CCFs and CCFs' overall contribution to ozone concentrations is still at the early stages. Thus, (10) more downwind measurements of concentrations of photooxidized terpene products and ozone will provide valuable information. This effort could then be followed by (11) laboratory exploration of reaction rates of terpenes and other identified odorous compounds with key atmospheric oxidants. Furthermore, findings could be incorporated to generate (12) improved chemical mechanisms for atmospheric dispersion models and chemical transport models. Another application is (13) modeling studies of odor persistence with decay of terpenes due to reactions in the troposphere, as well as (14) validation studies of modeled concentrations of tracer compounds (e.g., β-myrcene and β-myrcene photooxidized products).

6.5. Understanding the Health Impacts Indoors and Outdoors. Although some aspects of indoor air quality have been studied, there is still opportunity for guidelines dedicated to cannabis-related terpene exposure. Importantly, the health effects of exposure to cannabis-related terpenes for those living near facilities are not yet understood. A (15) cluster analysis of chemical compound concentrations and health effects, under short-term and long-term exposure, is needed. This analysis should consider additional factors such as gender, socioeconomic status, and other indicators. Moreover, since a multiplicity of commercial strains exist and each has its particular odorous emissions, (16) an analysis of how communities develop symptoms in reaction to CCFs odors is required.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c06372.

> Section S1, complete comparison of odor emission factors between cannabis industry and wastewater treatment, municipal solid waste treatment, and livestock operations; Section S2, graphical illustration of CAPEX and OPEX differences for BATs discussed in manuscript; Section S3, discusses possible primary and secondary pollutant tracers of CCF emissions; and Section S4, results from pollen measurements and microorganisms from CCFs, also of interest to regulators (PDF)

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Notes

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■ GLOSSARY

Cannabacea	family of cannabis plants
Cannabis	genus of cannabis plants
Cannabis sativa	species of cannabis plants with low (<0.3%) THC content
Cannabis indica	species of cannabis plants with high (>0.3%) THC content
Hemp	subspecies of *Cannabis sativa* cultivated for fiber and seed production
Marijuana	subspecies of *Cannabis indica* cultivated for drug production
Wild cannabis	subspecies of either *C. indica/sativa* that grows in the wild
Cannabis cultivation facility	industry dedicated to the growth of either hemp or marijuana that may or may not process the harvested plants into the final product
Indoor growing	cannabis is grown in enclosed spaces with mechanical ventilation with or without control equipment
Greenhouse growing	cannabis is grown in semiopen spaces with or without mechanical ventilation and control equipment
Outdoor growing	cannabis is grown in open spaces without mechanical ventilation and control equipment.

■ REFERENCES

(1) Klumpers, L. E.; Thacker, D. L. A brief background on cannabis: From plant to medical indications. *Journal of AOAC International* **2019**, *102*, 412−420.

(2) AROYA, Cannabis Legalization Status in the US by State. 2021. https://aroya.io/resources/weed-legalization-map-legalization-status-2021-united-states/ (accessed 2021-11-20).

(3) Fischer, B.; Russell, C.; Boyd, N. *Legalizing Cannabis. Experiences Lessons and Scenarios*; 2020; pp 89−115.
(4) CBD Choice, Countries With Legal Cannabis: An International Overview. 2021. https://cbdchoice.com/countries-with-legal-cannabis-an-international-overview/ (accessed 2021-11-20).
(5) Strunk, C. D. Yes to Cannabis ! Just Not in My Backyard An Analysis of Odor-Based. *Brief* **2020**, *49*, 32−37.
(6) Samburova, V.; McDaniel, M.; Campbell, D.; Wolf, M.; Stockwell, W. R.; Khlystov, A. Dominant volatile organic compounds (VOCs) measured at four Cannabis growing facilities: Pilot study results. *J. Air Waste Manage. Assoc.* **2019**, *69*, 1267−1276.
(7) Wang, C.-T.; Wiedinmyer, C.; Ashworth, K.; Harley, P. C.; Ortega, J.; Rasool, Q. Z.; Vizuete, W. Potential regional air quality impacts of cannabis cultivation facilities in Denver, Colorado. *Atmospheric Chemistry and Physics* **2019**, *19*, 13973−13987.
(8) Rohr, A. C. The health significance of gas- and particle-phase terpene oxidation products: A review. *Environ. Int.* **2013**, *60*, 145−162.
(9) Couch, J. R.; Grimes, G. R.; Wiegand, D. M.; Green, B. J.; Glassford, E. K.; Zwack, L. M.; Lemons, A. R.; Jackson, S. R.; Beezhold, D. H. Potential occupational and respiratory hazards in a Minnesota cannabis cultivation and processing facility. *American Journal of Industrial Medicine* **2019**, *62*, 874−882.
(10) Couch, J. R.; Grimes, G. R.; Green, B. J.; Wiegand, D. M.; King, B.; Methner, M. M. Review of NIOSH Cannabis-Related Health Hazard Evaluations and Research. *Annals of Work Exposures and Health* **2020**, *64*, 693−704.
(11) Metro Vancouver, *A Proposed Emission Regulation for Cannabis Production and Processing Operations in Metro Vancouver*; 2019.
(12) Public Health Ontario, *Odours from cannabis production*; 2018; pp 1−10.
(13) Denver Public Health and Environment, *Canabis Environmental Best Management Practices Guide*; 2018.
(14) Ashworth, K.; Vizuete, W. High Time to Assess the Environmental Impacts of Cannabis Cultivation. *Environ. Sci. Technol.* **2017**, *51*, 2531−2533.
(15) Wartenberg, A. C.; Holden, P. A.; Bodwitch, H.; Parker-Shames, P.; Novotny, T.; Harmon, T. C.; Hart, S. C.; Beutel, M.; Gilmore, M.; Hoh, E.; Butsic, V. Cannabis and the Environment: What Science Tells Us and What We Still Need to Know. *Environ. Sci. Technol. Lett.* **2021**, *8*, 98−107.
(16) Zheng, Z.; Fiddes, K.; Yang, L. A narrative review on environmental impacts of cannabis cultivation. *Journal of Cannabis Research* **2021**, *3*, 35.
(17) Colorado Government - Cannabis, Home grow laws - Colorado, US. 2021. https://cannabis.colorado.gov/legal-marijuana-use/home-grow-laws (accessed 2021-11-20).
(18) Colorado General Assembly, First Regular Session, 73rd General Assembly, HB21-1301 Cannabis Outdoor Cultivation Measures. 2021. https://leg.colorado.gov/sites/default/files/2021a_1301_signed.pdf (accessed 2021-11-20).
(19) Wang, C. T.; Wiedinmyer, C.; Ashworth, K.; Harley, P. C.; Ortega, J.; Vizuete, W. Leaf enclosure measurements for determining volatile organic compound emission capacity from Cannabis spp. *Atmos. Environ.* **2019**, *199*, 80−87.
(20) Upland Agricultural Consulting, *Commercial Cannabis Production in British Columbia: Best Available Control Technologies and Regulatory Oversight of Environmental Considerations*; 2019; p 87.
(21) McGowan, M. K. Load calculations for cannabis grow facilities. *ASHRAE J.* **2020**, *62*, 83−87.
(22) Wang, C. T.; Ashworth, K.; Wiedinmyer, C.; Ortega, J.; Harley, P. C.; Rasool, Q. Z.; Vizuete, W. Ambient measurements of monoterpenes near Cannabis cultivation facilities in Denver, Colorado. *Atmos. Environ.* **2020**, *232*, 117510.
(23) Raharjo, T. J.; Verpoorte, R. Methods for the analysis of cannabinoids in biological materials: A review. *Phytochemical Analysis* **2004**, *15*, 79−94.
(24) Micalizzi, G.; Vento, F.; Alibrando, F.; Donnarumma, D.; Dugo, P.; Mondello, L. Cannabis Sativa L.: a comprehensive review on the analytical methodologies for cannabinoids and terpenes characterization. *Journal of Chromatography A* **2021**, *1637*, 461864.
(25) Farag, S.; Kayser, O. Cultivation and Breeding of Cannabis sativa L. for Preparation of Standardized Extracts for Medicinal Purposes; *Medicinal and Aromatic Plants of the World*; 2015; pp 165−186, DOI: 10.1007/978-94-017-9810-5_9.
(26) Tholl, D.; Boland, W.; Hansel, A.; Loreto, F.; Röse, U. S.; Schnitzler, J. P. Practical approaches to plant volatile analysis. *Plant Journal* **2006**, *45*, 540−560.
(27) Hood, L. V. S.; Dames, M. E.; Barry, G. T. Headspace Volatiles of Marijuana. *Nature* **1973**, *242*, 402−403.
(28) Rothschild, M.; Bergström, G.; Wängberg, S. Å. Cannabis sativa: Volatile compounds from pollen and entire male and female plants of two variants, Northern Lights and Hawaian Indica. *Botanical Journal of the Linnean Society* **2005**, *147*, 387−397.
(29) Wiebelhaus, N.; Hamblin, D.; Kreitals, N. M.; Almirall, J. R. Differentiation of marijuana headspace volatiles from other plants and hemp products using capillary microextraction of volatiles (CMV) coupled to gas-chromatography−mass spectrometry (GC−MS). *Forensic Chemistry* **2016**, *2*, 1−8.
(30) Bueno, J.; Leuer, E.; Kearney, M.; Green, E. H.; Greenbaum, E. A. The preservation and augmentation of volatile terpenes in cannabis inflorescence. *J. Cannabis Res.* **2020**, *2*, 27.
(31) Knights, R. L. *Terpene Odors Escaping From Cannabis Growing*; The Cannabis Science Conference, Portland, 2017; pp 1−6.
(32) Martyny, J. W.; Serrano, K. A.; Schaeffer, J. W.; Van Dyke, M. V. Potential exposures associated with indoor marijuana growing operations. *Journal of Occupational and Environmental Hygiene* **2013**, *10*, 622−639.
(33) Silvey, B.; Seto, E.; Gipe, A.; Ghodsian, N.; Simpson, C. D. Occupational exposure to particulate matter and volatile organic compounds in two indoor cannabis production facilities. *Annals of Work Exposures and Health* **2020**, *64*, 715−727.
(34) Sherma, J.; Rabel, F. Thin layer chromatography in the analysis of cannabis and its components and synthetic cannabinoids. *Journal of Liquid Chromatography and Related Technologies* **2019**, *42*, 613−628.
(35) Jordan, A.; Haidacher, S.; Hanel, G.; Hartungen, E.; Märk, L.; Seehauser, H.; Schottkowsky, R.; Sulzer, P.; Märk, T. D. A high resolution and high sensitivity proton-transfer-reaction time-of-flight mass spectrometer (PTR-TOF-MS). *Int. J. Mass Spectrom.* **2009**, *286*, 122−128.
(36) Li, H.; Riva, M.; Rantala, P.; Heikkinen, L.; Daellenbach, K.; Krechmer, J. E.; Flaud, P. M.; Worsnop, D.; Kulmala, M.; Villenave, E.; Perraudin, E.; Ehn, M.; Bianchi, F. Terpenes and their oxidation products in the French Landes forest: Insights from Vocus PTR-TOF measurements. *Atmospheric Chemistry and Physics* **2020**, *20*, 1941−1959.
(37) Han, C.; Liu, R.; Luo, H.; Li, G.; Ma, S.; Chen, J.; An, T. Pollution profiles of volatile organic compounds from different urban functional areas in Guangzhou China based on GC/MS and PTR-TOF-MS: Atmospheric environmental implications. *Atmos. Environ.* **2019**, *214*, 116843.
(38) Rice, S.; Koziel, J. A. The relationship between chemical concentration and odor activity value explains the inconsistency in making a comprehensive surrogate scent training tool representative of illicit drugs. *Forensic Science International* **2015**, *257*, 257−270.
(39) Rice, S.; Koziel, J. A. Characterizing the Smell of Marijuana by Odor Impact of Volatile Compounds: An Application of Simultaneous Chemical and Sensory Analysis. *PLoS One* **2015**, *10*, e0144160.
(40) Mazian, B.; Cariou, S.; Chaignaud, M.; Fanlo, J. L.; Fauconnier, M. L.; Bergeret, A.; Malhautier, L. Evolution of temporal dynamic of volatile organic compounds (VOCs) and odors of hemp stem during field retting. *Planta* **2019**, *250*, 1983−1996.
(41) USEPA, *Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air*, EPA/625/R-96/010b, 2nd ed.; 1999; pp 1−63.
(42) USEPA, *Technical Assistance Document for Sampling and Analysis of Ozone Precursors for the Photochemical Assessment Monitoring Stations Program - Revision 2 - April 2019*; 2019; 256pp.

(43) NIOSH, Terpenes 1552. Measurement. In *NIOSH Manual of Analytical Methods (NMAM)*, 4th ed.; 1996; pp 13−16.
(44) USEPA, Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air Second Edition Compendium Method TO-17 Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling Onto Sorbent Tubes. 1999. https://www.epa.gov/sites/default/files/2019-11/documents/to-17r.pdf (accessed 2022-02-02).
(45) Khan, M. F.; Sahani, M.; Nadzir, M. S. M.; Yik, L. C.; Hoque, H. M. S.; Hamid, H. H. A.; Wahab, M. A. I.; Munna, F. T.; Amin, N.; Misran, H.; Akhtaruzzaman, M.; Maulud, K. N. A.; Juahir, H.; Ghazali, A.; Ismail, A. Volatile Organic Compound Analysis by Sorbent Tube-Thermal Desorption-Gas Chromatography: A Review. *Int. J. Eng. Technol. (Bremen, Ger.)* **2018**, *7*, 165−175.
(46) Bax, C.; Sironi, S.; Capelli, L. How can odors be measured? An overview of methods and their applications. *Atmosphere* **2020**, *11*, 92.
(47) Brancher, M.; Griffiths, K. D.; Franco, D.; de Melo Lisboa, H. A review of odour impact criteria in selected countries around the world. *Chemosphere* **2017**, *168*, 1531−1570.
(48) Bokowa, A.; Diaz, C.; Koziel, J. A.; McGinley, M.; Barclay, J.; Schauberger, G.; Guillot, J. M.; Sneath, R.; Capelli, L.; Zorich, V.; Izquierdo, C.; Bilsen, I.; Romain, A. C.; Del Carmen Cabeza, M.; Liu, D.; Both, R.; Van Belois, H.; Higuchi, T.; Wahe, L. Summary and overview of the odour regulations worldwide. *Atmosphere* **2021**, *12*, 206.
(49) Capelli, L.; Sironi, S.; Del Rosso, R. Odour emission factors: Fundamental tools for air quality management. *Chemical Engineering Transactions* **2014**, *40*, 193−198.
(50) Invernizzi, M.; Brancher, M.; Sironi, S.; Capelli, L.; Piringer, M.; Schauberger, G. Odour impact assessment by considering short-term ambient concentrations: A multi-model and two-site comparison. *Environ. Int.* **2020**, *144*, 105990.
(51) Invernizzi, M.; Capra, F.; Sozzi, R.; Capelli, L.; Sironi, S. Development and Evaluation of a Fluctuating Plume Model for Odor Impact Assessment. *Applied Sciences* **2021**, *11*, 3310.
(52) Brancher, M.; Hieden, A.; Baumann-Stanzer, K.; Schauberger, G.; Piringer, M. Performance evaluation of approaches to predict sub-hourly peak odour concentrations. *Atmospheric Environment: X* **2020**, *7*, 100076.
(53) Cartelle, D.; Bao, M.; Casas, C.; Sostenibles, T. S. Estimation of Short Odor Events by Using Chemically Reactive Odorants Atmospheric Dispersion Modelling Around a Pulp Paper Mill. *17th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Harmo 2019* **2016**, *1*, 1−6.
(54) Zhang, Y.; Kacira, M.; An, L. A CFD study on improving air flow uniformity in indoor plant factory system. *Biosystems Engineering* **2016**, *147*, 193−205.
(55) Benni, S.; Tassinari, P.; Bonora, F.; Barbaresi, A.; Torreggiani, D. Efficacy of greenhouse natural ventilation: Environmental monitoring and CFD simulations of a study case. *Energy and Buildings* **2016**, *125*, 276−286.
(56) Klancoowat, W.; Chaiyat, N.; Nathewet, P. Thermal Performance of Wastewater Recovery from Air Conditioning for Cannabis Production. *The third international conference on environmental development administration 2020 "Environmental Struggles and the Way Forward*; 2020; pp 100−109.
(57) Bartzanas, T.; Kacira, M.; Zhu, H.; Karmakar, S.; Tamimi, E.; Katsoulas, N.; Lee, I. B.; Kittas, C. Computational fluid dynamics applications to improve crop production systems. *Computers and Electronics in Agriculture* **2013**, *93*, 151−167.
(58) Sørensen, D. N.; Weschler, C. J. Modeling-gas phase reactions in indoor environments using computational fluid dynamics. *Atmos. Environ.* **2002**, *36*, 9−18.
(59) Carter, W. P. Development of a database for chemical mechanism assignments for volatile organic emissions. *J. Air Waste Manage. Assoc.* **2015**, *65*, 1171−1184.
(60) Atkinson, R.; Arey, J. Gas-phase tropospheric chemistry of biogenic volatile organic compounds: A review. *Atmos. Environ.* **2003**, *37*, 197−219.
(61) Schwantes, R.; Emmons, L.; Orlando, J.; Barth, M.; Tyndall, G.; Hall, S.; Ullmann, K.; St. Clair, J.; Blake, D.; Wisthaler, A.; Bui, T. Comprehensive isoprene and terpene chemistry improves simulated surface ozone in the southeastern U.S. *Atmospheric Chemistry and Physics Discussions* **2020**, *20*, 3739−3776.
(62) Henderson, B. H.; Jeffries, H. E.; Kim, B. U.; Vizuete, W. G. The influence of model resolution on ozone in industrial volatile organic compound plumes. *J. Air Waste Manage. Assoc.* **2010**, *60*, 1105−1117.
(63) Maher, R.; Bhandari, S.; de Ferreyro Monticelli, D.; Eykelbosh, A.; Henderson, S. B.; Zimmerman, N.; Giang, A. Understanding the urban smellscape: Developing a screening method for odour source identification using citizen science and back trajectory modelling. *ISES2021: Multisector Engagement for Addressing Emerging Environmental Exposures*; 2021.
(64) Stein, A. F.; Draxler, R. R.; Rolph, G. D.; Stunder, B. J.; Cohen, M. D.; Ngan, F. Noaa's hysplit atmospheric transport and dispersion modeling system. *Bulletin of the American Meteorological Society* **2015**, *96*, 2059−2077.
(65) Jiang, G.; Lamb, B.; Westberg, H. Using back trajectories and process analysis to investigate photochemical ozone production in the Puget Sound region. *Atmos. Environ.* **2003**, *37*, 1489−1502.
(66) Gloss, D. An Overview of Products and Bias in Research. *Neurotherapeutics* **2015**, *12*, 731−734.
(67) Metro Vancouver, *Exploring Options to Manage Emissions from Cannabis Production and Processing Operations in Metro Vancouver: Cannabis Cultivation Emissions Estimate Methodology and Sensitivity Analysis*; 2019.
(68) Gentner, D. R.; Ormeño, E.; Fares, S.; Ford, T. B.; Weber, R.; Park, J. H.; Brioude, J.; Angevine, W. M.; Karlik, J. F.; Goldstein, A. H. Emissions of terpenoids, benzenoids, and other biogenic gas-phase organic compounds from agricultural crops and their potential implications for air quality. *Atmospheric Chemistry and Physics* **2014**, *14*, 5393−5413.
(69) Hartman, M.; Humphreys, H.; Burack, J.; Lambert, K.; Martin, P. MED 2018 Mid-Year Update - Colorado. 2021. https://sbg.colorado.gov/sites/sbg/files/MED2018MidYearUpdate.pdf (accessed 2021-11-20).
(70) Allen, K. D.; McKernan, K.; Pauli, C.; Roe, J.; Torres, A.; Gaudino, R. Genomic characterization of the complete terpene synthase gene family from Cannabis sativa. *PLoS One* **2019**, *14*, e0222363.
(71) Oswald, I. W.; Ojeda, M. A.; Pobanz, R. J.; Koby, K. A.; Buchanan, A. J.; Del Rosso, J.; Guzman, M. A.; Martin, T. J. Identification of a New Family of Prenylated Volatile Sulfur Compounds in Cannabis Revealed by Comprehensive Two-Dimensional Gas Chromatography. *ACS Omega* **2021**, *6*, 31667−31676.
(72) Bowman, J. H.; Barket, D. J.; Shepson, P. B. Atmospheric chemistry of nonanal. *Environ. Sci. Technol.* **2003**, *37*, 2218−2225.
(73) Gilbert, A. N.; DiVerdi, J. A. Use of rating scales versus check-all-that-apply ballots in quantifying strain-specific Cannabis aroma. *J. Sens. Stud.* **2019**, *34*, e12499.
(74) SC Labs, Six primary terpenes groups for classification of cannabis and hemp. 2020. https://www.sclabs.com/wp-content/uploads/2020/11/Terpenoid-Infographic-MKT00358.pdf (accessed 2021-08-12).
(75) Eltarkawe, M.; Miller, S. Industrial odor source identification based on wind direction and social participation. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1242.
(76) BCX Environmental Consulting, *Odour Impact Assessment for a Medical Marihuana Grow Facility*; 436 Huron Road, 2020; p 40.
(77) BCX Environmental Consulting, *Odour Impact Assessment for a Medical Marihuana Grow Facility*; 199 Anglesea Street, 2020; p 41.
(78) RWDI AIR Inc., *Wilmot Creek Secondary Plan - Municipality of Clarington*; Air Quality Feasibility Assessment, Ontario, 2018.
(79) Delikhoon, M.; Fazlzadeh, M.; Sorooshian, A.; Baghani, A. N.; Golaki, M.; Ashournejad, Q.; Barkhordari, A. Characteristics and health effects of formaldehyde and acetaldehyde in an urban area in Iran. *Environ. Pollut.* **2018**, *242*, 938−951.

(80) Seinfeld, J. H.; Pandis, S. N. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*, 2nd ed.; 2006; pp 628−674.
(81) Iinuma, Y.; Böge, O.; Miao, Y.; Sierau, B.; Gnauk, T.; Herrmann, H. Laboratory studies on secondary organic aerosol formation from terpenes. *Faraday Discuss.* **2005**, *130*, 279−294.
(82) Ishizuka, Y.; Tokumura, M.; Mizukoshi, A.; Noguchi, M.; Yanagisawa, Y. Measurement of secondary products during oxidation reactions of terpenes and ozone based on the PTR-MS analysis: Effects of coexistent carbonyl compounds. *International Journal of Environmental Research and Public Health* **2010**, *7*, 3853−3870.
(83) Lee, A.; Goldstein, A. H.; Keywood, M. D.; Gao, S.; Varutbangkul, V.; Bahreini, R.; Ng, N. L.; Flagan, R. C.; Seinfeld, J. H. Gas-phase products and secondary aerosol yields from the ozonolysis of ten different terpenes. *J. Geophys. Res.* **2006**, *111*, D07302.
(84) Schuetzle, D.; Rasmussen, R. A. The Molecular Composition of Secondary Aerosol Particles Formed from Terpenes. *Journal of the Air Pollution Control Association* **1978**, *28*, 236−240.
(85) Rohr, A. C.; Weschler, C. J.; Koutrakis, P.; Spengler, J. D. Generation and quantification of ultrafine particles through terpene/ozone reaction in a chamber setting. *Aerosol Sci. Technol.* **2003**, *37*, 65−78.
(86) Wainman, T.; Zhang, J.; Weschler, C. J.; Lioy, P. J. Ozone and limonene in indoor air: A source of submicron particle exposure. *Environ. Health Perspect.* **2000**, *108*, 1139−1145.
(87) Presto, A. A.; Huff Hartz, K. E.; Donahue, N. M. Secondary organic aerosol production from terpene ozonolysis. 2. Effect of NOx concentration. *Environ. Sci. Technol.* **2005**, *39*, 7046−7054.
(88) Kavouras, I. G.; Mihalopoulos, N.; Stephanou, E. G. Formation of atmospheric particles from organic acids produced by forests. *Nature* **1998**, *395*, 683−686.
(89) O'Dowd, C. D.; Aalto, P.; Hämeri, K.; Kulmala, M.; Hoffmann, T. Atmospheric particles from organic vapours. *Nature* **2002**, *416*, 497−498.
(90) Salvador, C. M.; Chou, C. C.; Ho, T. T.; Tsai, C. Y.; Tsao, T. M.; Tsai, M. J.; Su, T. C. Contribution of terpenes to ozone formation and secondary organic aerosols in a subtropical forest impacted by urban pollution. *Atmosphere* **2020**, *11*, 1232.
(91) Koch, S.; Winterhalter, R.; Uherek, E.; Kolloff, A.; Neeb, P.; Moortgat, G. K. Formation of new particles in the gas-phase ozonolysis of monoterpenes. *Atmos. Environ.* **2011**, *34*, 4031.
(92) Atkinson, R.; Arey, J. Atmospheric Degradation of Volatile Organic Compounds. *Chem. Rev.* **2003**, *103*, 4605−4638.
(93) Böge, O.; Mutzel, A.; Iinuma, Y.; Yli-Pirilä, P.; Kahnt, A.; Joutsensaari, J.; Herrmann, H. Gas-phase products and secondary organic aerosol formation from the ozonolysis and photooxidation of myrcene. *Atmos. Environ.* **2013**, *79*, 553−560.
(94) Zhu, W.; Guo, S.; Hu, M.; Zhang, Z.; Wang, H.; Yu, Y.; Chen, Z.; Shen, R.; Tan, R.; Song, K.; Liu, K.; Tang, R.; Liu, Y.; Lou, S.; Li, Y.; Zhang, W.; Zhang, Z.; Shuai, S.; Xu, H.; Li, S.; Chen, Y.; Canonaco, F.; Prévôt, A. Mass spectral characterization of secondary organic aerosol from urban lifestyle sources emissions. *Atmos. Chem. Phys.* **2021**, *21*, 15065.
(95) Kroll, J. H.; Heald, C. L.; Cappa, C. D.; Farmer, D. K.; Fry, J. L.; Murphy, J. G.; Steiner, A. L. The complex chemical effects of COVID-19 shutdowns on air quality. *Nat. Chem.* **2020**, *12*, 777−779.
(96) Summers, H. M.; Sproul, E.; Quinn, J. C. The greenhouse gas emissions of indoor cannabis production in the United States. *Nat. Sustain.* **2021**, *4*, 644.
(97) Mills, E. The carbon footprint of indoor Cannabis production. *Energy Policy* **2012**, *46*, 58−67.
(98) Mills, E. Comment on "Cannabis and the Environment: What Science Tells Us and What We Still Need to Know. *Environ. Sci. Technol. Lett.* **2021**, *8*, 483.
(99) Mehboob, N.; Farag, H. E. Z.; Sawas, A. M. Energy Consumption Model for Indoor Cannabis Cultivation Facility. *IEEE Open Access Journal of Power and Energy* **2020**, *7*, 222−233.
(100) Britigan, N.; Alshawa, A.; Nizkorodov, S. A. Quantification of ozone levels in indoor environments generated by ionization and ozonolysis air purifiers. *J. Air Waste Manage. Assoc.* **2006**, *56*, 601−610.
(101) Taylor, A.; Birkett, J. W. Pesticides in cannabis: A review of analytical and toxicological considerations. *Drug Testing and Analysis* **2020**, *12*, 180−190.
(102) Fishwick, D.; Allan, L. J.; Wright, A.; Barber, C. M. Respiratory symptoms, lung function and cell surface markers in a group of hemp fiber processors. *Am. J. Ind. Med.* **2001**, *39*, 419−425.
(103) Fishwick, D.; Allan, L. J.; Wright, A.; Curran, A. D. Assessment of exposure to organic dust during hemp processing. *Annals of Occupational Hygene* **2001**, *45*, 577−583.
(104) Zuskin, E.; Kanceljak, B.; Pokrajac, D.; Schachter, E. N.; Witek, T. J. Respiratory symptoms and lung function in hemp workers. *British Journal of Industrial Medicine* **1990**, *47*, 627−632.
(105) Davidson, M.; Reed, S.; Oosthuizen, J.; O'Donnell, G.; Gaur, P.; Cross, M.; Dennis, G. Occupational health and safety in cannabis production: an Australian perspective. *International Journal of Occupational and Environmental Health* **2018**, *24*, 75−85.
(106) Sack, C.; Ghodsian, N.; Jansen, K.; Silvey, B.; Simpson, C. D. Allergic and respiratory symptoms in employees of indoor cannabis grow facilities. *Annals of Work Exposures and Health* **2020**, *64*, 754−764.
(107) Kephalopoulos, S.; Kotzias, D.; Koistinen, K.; Carslaw, N.; Carrer, P.; Fossati, S.; Hoffmann, T.; Langer, S.; Larsen, B.; Monn, C.; Nicolas, M.; Salthammer, T.; Schlitt, C.; Winterhalter, R.; Wolkoff, P. *Impact of Ozone-initiated Terpene Environment and Quality of Life*; 2007.
(108) Trantallidi, M.; Dimitroulopoulou, C.; Wolkoff, P.; Kephalopoulos, S.; Carrer, P. EPHECT III: Health risk assessment of exposure to household consumer products. *Science of The Total Environment* **2015**, *536*, 903−913.
(109) Centers for Disease Control and Prevention, Flavorings-Related Lung Disease: Occupational Exposure Limits. 2004. https://www.cdc.gov/niosh/topics/flavorings/limits.html (accessed 2021-08-14).
(110) Rohr, A. C.; Wilkins, C. K.; Clausen, P. A.; Hammer, M.; Nielsen, G. D.; Wolkoff, P.; Spengler, J. D. Upper Airway and Pulmonary Effects of Oxidation Products of (+)- α-pinene, d-limonene, and Isoprene in Balb Mice. *Inhalation Toxicology* **2002**, *14*, 663−684.
(111) Metro Vancouver, *Regional ground-level ozone strategy for the Canadian Lower Fraser Valley Region*; 2014.
(112) World Health Organization, *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide - Global update 2005*; 2005.
(113) Hayes, J. E.; Stevenson, R. J.; Stuetz, R. M. Survey of the effect of odour impact on communities. *Journal of Environmental Management* **2017**, *204*, 349−354.
(114) Blanes-Vidal, V.; Suh, H.; Nadimi, E. S.; Løfstrøm, P.; Ellermann, T.; Andersen, H. V.; Schwartz, J. Residential exposure to outdoor air pollution from livestock operations and perceived annoyance among citizens. *Environ. Int.* **2012**, *40*, 44−50.
(115) Blanes-Vidal, V.; Nadimi, E. S.; Ellermann, T.; Andersen, H. V.; Løfstrøm, P. Perceived annoyance from environmental odors and association with atmospheric ammonia levels in non-urban residential communities: A cross-sectional study. *Environmental Health: A Global Access Science Source* **2012**, *11*, 27.
(116) Aatamila, M.; Verkasalo, P. K.; Korhonen, M. J.; Viluksela, M. K.; Pasanen, K.; Tiittanen, P.; Nevalainen, A. Odor annoyance near waste treatment centers: A population-based study in Finland. *J. Air Waste Manage. Assoc.* **2010**, *60*, 412−418.
(117) Badach, J.; Kolasińska, P.; Paciorek, M.; Wojnowski, W.; Dymerski, T.; Gębicki, J.; Dymnicka, M.; Namieśnik, J. A case study of odour nuisance evaluation in the context of integrated urban planning. *Journal of Environmental Management* **2018**, *213*, 417−424.
(118) Wroniszewska, A.; Zwoździak, J. Odor annoyance assessment by using logistic regression on an example of the municipal sector. *Sustainability (Switzerland)* **2020**, *12*, 6102.

(119) Nordin, S.; Lidén, E. Environmental odor annoyance from air pollution from steel industry and bio-fuel processing. *Journal of Environmental Psychology* **2006**, *26*, 141−145.
(120) Hayes, J. E.; Stevenson, R. J.; Stuetz, R. M. The impact of malodour on communities: A review of assessment techniques. *Sci. Total Environ.* **2014**, *500*−*501*, 395−407.
(121) Conti, C.; Guarino, M.; Bacenetti, J. Measurements techniques and models to assess odor annoyance: A review. *Environ. Int.* **2020**, *134*, 105261.
(122) Nordin, S.; Aldrin, L.; Claeson, A. S.; Andersson, L. Effects of negative affectivity and odor valence on chemosensory and symptom perception and perceived ability to focus on a cognitive task. *Perception* **2017**, *46*, 431−446.
(123) Schiffman, S. S.; Miller, E. A. S.; Suggs, M. S.; Graham, B. G. The Effect of Environmental Odors Emanating from Commercial Swine Operations on the Mood of Nerby Residents. *Brain Res. Bull.* **1995**, *37*, 369−375.
(124) Morgan, B.; Hansgen, R.; Hawthorne, W.; Miller, S. L. Industrial odor sources and air pollutant concentrations in Globeville, a Denver, Colorado neighborhood. *J. Air Waste Manage. Assoc.* **2015**, *65*, 1127−1140.
(125) Shusterman, D.; Lipscomb, J.; Neutra, R.; Satin, K. Symptom prevalence and odor-worry interaction near hazardous waste sites. *Environ. Health Perspect.* **1991**, *94*, 25−30.
(126) Colorado Department of Health and Environment, *Guide to Worker Safety and Health in the Marijuana Industry*; 2017.
(127) California OSHA, Cannabis Industry Health and Safety. 2021. https://www.dir.ca.gov/dosh/cannabis-industry-health-and-safety.html (accessed 2021-08-17).
(128) WorkSafe BC, *Health and safety in cannabis cultivation*; 2021; p 7.
(129) Ontario Work Safety and Prevention Services, Cannabis Production: Health and Safety Issues. 2021. https://www.wsps.ca/Information-Resources/Topics/Cannabis-Production.aspx (accessed 2021-08-17).
(130) Simpson, C. Occupational health and safety in the cannabis industry. *Annals of Work Exposures and Health* **2020**, *64*, 677−678.
(131) Rotermann, M. Looking back from 2020, how cannabis use and related behaviours changed in Canada. *Health Rep.* **2021**, *32*, 3−14.
(132) McDonald, B. C.; De Gouw, J. A.; Gilman, J. B.; Jathar, S. H.; Akherati, A.; Cappa, C. D.; Jimenez, J. L.; Lee-Taylor, J.; Hayes, P. L.; McKeen, S. A.; Cui, Y. Y.; Kim, S. W.; Gentner, D. R.; Isaacman-VanWertz, G.; Goldstein, A. H.; Harley, R. A.; Frost, G. J.; Roberts, J. M.; Ryerson, T. B.; Trainer, M. Volatile chemical products emerging as largest petrochemical source of urban organic emissions. *Science* **2018**, *359*, 760−764.
(133) Eykelbosh, A.; Maher, R.; de Ferreyro Monticelli, D.; Ramkairsingh, A.; Henderson, S.; Giang, A.; Zimmerman, N. Elucidating the community health impacts of odours using citizen science and mobile monitoring. *Environmental Health Review* **2021**, *64* (2), 24−27.
(134) Hsu, Y. C.; Tasota, M.; Cross, J.; Dias, B.; Dille, P.; Sargent, R.; Huang, T. H.; Nourbakhsh, I. Smell pittsburgh: Community-Empowered mobile smell reporting system. *arXiv* **2019**, 65−79.
(135) Lotesoriere, B. J.; Giacomello, A. D.; Bax, C.; Capelli, L. The Italian Pilot Study of the D-NOSES Project: an Integrated Approach Involving Citizen Science and Olfactometry to Identify Odour Sources in the area of Castellanza (VA). *Chem. Eng. J.* **2021**, *85*, 145−150.
(136) Lim, T. T.; Heber, A. J.; Ni, J.-Q.; Grant, R.; Sutton, A. L. Odor Impact Distance Guideline for Swine Production Systems. *Proceedings of the Water Environment Federation* **2000**, *2000*, 773−788.
(137) USEPA, 2017 National Emissions Inventory (NEI) Data — Air Emissions Inventories. 2020. https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data (accessed 2021-07-22).
(138) Wen, M. Impacts of industrial and biogenic emissions on air quality. Ph.D. thesis, Washington State University, 2019.

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