

Potential occupational and respiratory hazards in a Minnesota cannabis cultivation and processing facility

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Abstract

Background: Cannabis has been legalized in some form for much of the United States. The National Institute for Occupational Safety and Health (NIOSH) received a health hazard evaluation request from a Minnesota cannabis facility and their union to undertake an evaluation.

Methods: NIOSH representatives visited the facility in August 2016 and April 2017. Surface wipe samples were collected for analysis of delta-9 tetrahydrocannabinol (Δ 9-THC), delta-9 tetrahydrocannabinol acid (Δ 9-THCA), cannabidiol, and cannabinol. Environmental air samples were collected for volatile organic compounds (VOCs), endotoxins (limulus amoebocyte lysate assay), and fungal diversity (NIOSH two-stage BC251 bioaerosol sampler with internal transcribed spacer region sequencing analysis).

Results: Surface wipe samples identified Δ 9-THC throughout the facility. Diacetyl and 2,3-pentanedione were measured in initial VOC screening and subsequent sampling during tasks where heat transference was greatest, though levels were well below the NIOSH recommended exposure limits. Endotoxin concentrations were highest during processing activities, while internal transcribed spacer region sequencing revealed that the Basidiomycota genus, *Wallemia*, had the highest relative abundance.

Conclusions: To the authors' knowledge, this is the first published report of potential diacetyl and 2,3-pentanedione exposure in the cannabis industry, most notably during cannabis decarboxylation. Endotoxin exposure was elevated during grinding, indicating that this is a potentially high-risk task. The findings indicate that potential health hazards of significance are present during cannabis processing, and employers should be aware of potential exposures to VOCs, endotoxin, and fungi. Further research into the degree of respiratory and dermal hazards and resulting health effects in this industry is recommended.

KEYWORDS

2,3-pentanedione, cannabis, diacetyl, endotoxin, fungi

Institution at which the work was performed: Division of Surveillance, Hazard Evaluations, and Field Studies, National Institute for Occupational Safety and Health, CDC.

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1 | INTRODUCTION

Cannabis, commonly known as marijuana, is classified as a Schedule 1 substance under the United States Drug Enforcement Administration's Controlled Substance Act.¹ However, 33 states and the District of Columbia have legalized cannabis for medicinal use only or medicinal and recreational use. In 2017, the cannabis industry employed over 120 000 people with projections of nearly 300 000 workers by 2021.² Thus, the cannabis industry is made up of a substantial workforce that may be at-risk of unknown or overlooked workforce exposures, due to limited characterization of hazards in the industry.

In August 2016, National Institute for Occupational Safety and Health (NIOSH) representatives responded to a management and union request for a health hazard evaluation at a Minnesota medical cannabis cultivation and processing facility to characterize potential occupational exposures. Occupational safety and health (OSH) concerns in cannabis production, which are similar to those traditionally associated with agriculture, are often addressed by state organizations charged with overseeing their respective cannabis programs.³⁻⁵ However, potential hazards including chemical and microbiological exposures unique to the cannabis industry have only recently been evaluated and require further characterization.⁶⁻⁹ The purpose of this evaluation was to characterize occupational exposures and add to the existing body of OSH literature in the legal emerging US cannabis harvesting and processing industry. Specifically, the authors aimed to characterize potential health hazards related to harvesting and processing of cannabis.

2 | MATERIALS AND METHODS

2.1 | Facility description

In response to the health hazard evaluation request, NIOSH representatives visited the facility in August 2016 and again in April 2017. The facility cultivates, harvests, and processes cannabis (*Cannabis sativa* L. *subsp sativa* and *Cannabis sativa* L. *subsp indica*) in both indoor and outdoor environments (Figure 1). Beginning with either seeds or mature donor plants grown indoors, production cannabis plants are moved throughout the facility during different life stages to maximize quality and growth. Maturing plants are moved either into indoor greenhouses or outdoor hoop houses (semicircular, fabric covered structures that allow sunlight penetration, and air movement). Mature plants are then harvested in stages. Large branches (known as colas) containing multiple flowers are separated and transferred to a drying area away from the growing rooms. Destemming consists of removing dried flowers from the cola with scissors or pruners. Dried flowers are then added to a grinder to produce a smaller, consistently sized product before being loaded into a decarboxylation oven (approximately 1.5 cubic feet) to convert delta-9 tetrahydrocannabinol acid

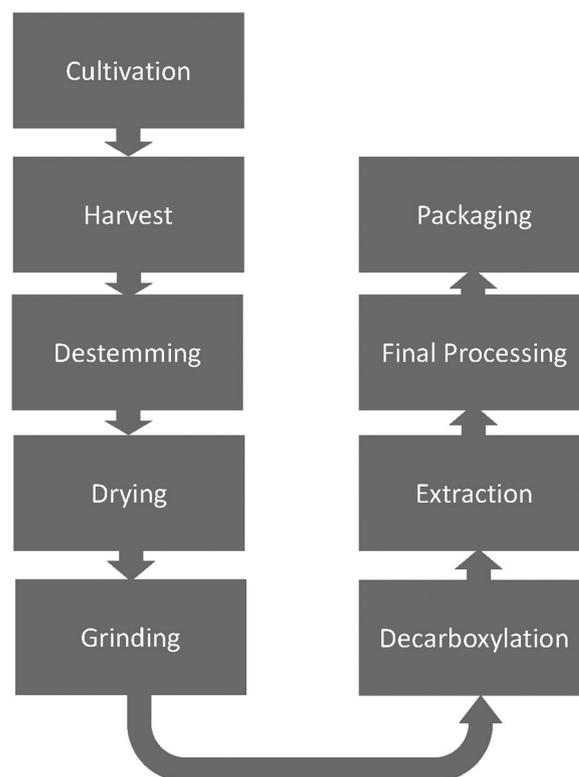


FIGURE 1 Flow diagram of cannabis production at the facility

($\Delta 9$ -THCA) into $\Delta 9$ -THC. The decarboxylated product is placed into a carbon dioxide extraction system to yield an oil which is sent to final processing and product packaging.

2.2 | Surface wipe sampling

Eighteen surface wipe samples for $\Delta 9$ -THC were collected using 4 in. \times 4 in. cotton twill wipes wetted with 3 mL of isopropyl alcohol. Where possible, a 100-square-centimeter (100 cm²) template was used to ensure consistent sampling technique. For each sample, the location and recent activities were noted. Surface wipe samples were analyzed by liquid chromatography and tandem mass spectrometry (LC-MSMS) (limit of detection = 4 ng per sample). Where possible, a second surface wipe was collected adjacent to the first for analysis of other phytocannabinoids ($\Delta 9$ -THCA, cannabidiol and cannabinol) in addition to $\Delta 9$ -THC, by high performance liquid chromatography with diode-array detection (HPLC-DAD; limit of detection = 2000 ng per sample). This method was modified from HPLC from the one used in a previously published manuscript.¹⁰ The $\Delta 9$ -THC only method is an established method in accordance with International Organization for Standardization 17025 requirements that has been internally developed by an American Industrial Hygiene Association accredited contract laboratory. Direct comparison of results from LC-MSMS ($\Delta 9$ -THC only) and HPLC-DAD (four cannabinoid) results is not possible because contamination across surfaces was often not equally distributed.

2.3 | Environmental and personal air sampling

2.3.1 | Volatile organic compounds

In August 2016, evacuated canisters (450 mL) with restricted flow controllers (6 hour, 15 minute, or instantaneous sample duration) were deployed to collect air samples for analysis of volatile organic compounds (VOCs) by gas chromatograph/mass spectrometer (GCMS). The method was modified to include a preconcentrator, as well as the addition of diacetyl, and 2,3-pentanedione to VOCs specifically measured.¹¹ In addition to evacuated canisters, personal and area sample collection was undertaken to specifically target diacetyl and 2,3-pentanedione according to Occupational Safety and Health Administration (OSHA) methods 1013 and 1016.^{12,13} The method was modified from the original gas chromatograph/mass spectrometer with flame ionization detector (GCMS-FID) to gas chromatograph/mass spectrometer operated in selected ion monitoring mode (GCMS-SIM) to increase the sensitivity of the method.¹⁴ Thermal desorption tubes (NIOSH Method 2549) were also sampled to further characterize VOCs in the environment.¹⁵

2.3.2 | Bioaerosols

Endotoxin personal and area aerosol samples were collected during the first site visit only. Personal full shift samples were collected during the entire work shift on four employees over 2 days ($n = 8$). Area samples were collected in various locations throughout the facility including in the vegetation room ($n = 2$), clone room ($n = 2$), greenhouse 1 ($n = 11$), greenhouse 2 ($n = 1$), hoophouse C ($n = 2$), hoophouse B ($n = 1$), loading dock ($n = 1$), and the breakroom ($n = 1$). The personal and area samples were taken at an air flow rate of 2 L/min onto three-piece 37-mm closed-face cassettes preloaded with 0.45- μm -pore-size endotoxin-free polycarbonate filter and analyzed for endotoxin content with the kinetic-chromogenic procedure using the limulus amoebocyte lysate assay (KC-LAL Assay) with a limit of detection of 0.5 endotoxin units (EU) (was 0.053 ng Endotoxin).¹⁶

Full-shift, personal samples ($n = 12$) and area aerosol samples ($n = 25$) were collected for the analysis of fungal community composition. The NIOSH two-stage BC251 bioaerosol sampler was used to sample fungal aerosols for approximately 8 hours at an air flow rate of 2 L/min as previously described.^{6,8} In August 2016, full-shift personal air samples were collected from four employees over 2 days ($n = 8$), and area sampling was undertaken ($n = 11$) in the same locations as for the endotoxin analysis with hoophouse samples representing outdoor grow exposures and greenhouse samples representing indoor grown exposures. In April 2017, personal full-shift sampling was undertaken with two employees over 2 days ($n = 4$) and area sampling in the same seven locations as previously over 2 days ($n = 14$). The composition of fungi in personal and area samples collected at the facility was characterized using internal transcribed spacer region sequencing. The extraction, primers, and sequencing instrument and process are described in a previous study

of bioaerosol exposures at a Washington State Cannabis production facility.⁶

3 | RESULTS

3.1 | Environmental THC contamination

Of the 18 surface wipe samples analyzed by LCMS-MS ($\Delta 9$ -THC, only), 15 (83%) had detectable amounts of $\Delta 9$ -THC, and varied from below the limit of detection to 53 000 ng per 100-square-centimeters ($\text{ng}/100 \text{ cm}^2$) as seen in Table 1. The highest concentrations of $\Delta 9$ -THC were near the decarboxylation oven for both the LCMS-MS (53 000 ng per 100 cm^2) and the HPLC-DAD (17 000 ng per 100 cm^2). Samples with no detectable $\Delta 9$ -THC were all collected in the breezeway area where minimal plant or cannabis products were observed.

For surface wipe samples analyzed for four cannabinoids by HPLC-DAD, results varied through the facility, with $\Delta 9$ -THCA typically higher in comparison to the $\Delta 9$ -THC (Table 1). For this method, 4 of 18 (22%) samples were positive for $\Delta 9$ -THC, 8 (44%) for $\Delta 9$ -THCA, 3 (17%) for cannabidiol and 2 (11%) for cannabinol.

While not directly comparable, the LCMS-MS ($\Delta 9$ -THC only) method detected $\Delta 9$ -THC in all but one sample location that the adjacent HPLC-DAD method (four cannabinoids) sample also had detectable $\Delta 9$ -THC or $\Delta 9$ -THCA concentrations. However, there were seven sample locations where the HPLC-DAD method did not detect either $\Delta 9$ -THC or $\Delta 9$ -THCA, whereas the LCMS-MS ($\Delta 9$ -THC only) method had detectable $\Delta 9$ -THC concentrations.

3.2 | Airborne VOCs

In August 2016, VOC screening (evacuated canister) area samples revealed low-levels of diacetyl (range: 1.6–23 parts per billion [ppb]) and 2,3-pentanedione (range: not detected–9.3 ppb). During the April 2017 visit, evacuated canister personal sampling focused on the decarboxylation task to further investigate the elevated levels observed in the 2016 area samples. NIOSH has set a recommended exposure limit (REL) for diacetyl of 5 ppb and 2,3-pentanedione of 9.3 ppb, both as a time-weighted average for up to 8 hour/day during a 40 hour work week.¹⁷ Diacetyl and 2,3-pentanedione were highest near the decarboxylation oven. Summary environmental area air sampling data for diacetyl and 2,3-pentanedione are presented in Table 2.

Diacetyl or 2,3-pentanedione exposures measured during April 2017 were all below the NIOSH RELs. Breathing zone sampling for diacetyl and 2,3-pentanedione using the OSHA method ranged from 0.36 to 0.51 ppb with the three detectable sample concentrations all between the minimum detectable concentration (0.29 ppb) and the minimum quantifiable concentration (1.07 ppb). All OSHA method area air samples ($N = 7$) were below detection limits except one sample for diacetyl near the decarboxylation oven that was between the minimum detectable concentration (0.30 ppb) and the minimum quantifiable concentration (1.03 ppb).

TABLE 1 Surface wipe sampling for cannabis compounds (ng per 100 cm²) in August 2016

Location	$\Delta 9$ -THC only	Four cannabinoid method			
	$\Delta 9$ -THC	$\Delta 9$ -THC	$\Delta 9$ -THCA	Cannabidiol	Cannabinol
Loading dock					
Workbench	160	ND	ND	ND	ND
Workbench #2	20	ND	ND	ND	ND
Decarboxylation oven desk	53 000	17 000	ND	[3,700]	[2,100]
Vegetation room					
Table under white board	470	ND	[5,300]	ND	ND
Refrigerator door ^a	[7,8]	ND	ND	ND	ND
Greenhouse A door handle ($\Delta 9$ -THC method only)	270	NA	NA	NA	NA
Greenhouse A door handle (Four cannabinoid method only)	NA	ND	[3600]	ND	ND
Greenhouse A					
PVC pipe supporting plants ^a	450	ND	[4,100]	ND	ND
Pallet jack ^a	1,500	ND	9,500	ND	ND
Sink	590	[4,400]	34,000	ND	ND
Greenhouse B					
PVC pipe supporting plants ^a	110	ND	ND	ND	ND
PVC pipe under filter ^a	[14]	ND	ND	ND	ND
Breezeway					
Storage cabinet Workbench	ND	8,000	140,000	[5,200]	[6,400]
Workbench near greenhouse	ND	ND	ND	ND	ND
Mobile cart near back door	ND	ND	ND	ND	ND
Storage crate-center of room	14,000	15,000	62,000	[3,900]	ND
Breakroom					
Counter near coffeemaker	24	ND	ND	ND	ND
Counter in front of microwave	71	ND	[2,400]	ND	ND
Table	26	ND	ND	ND	ND

Note: Values in brackets are between the limit of detection and limit of quantification. This means there is more uncertainty associated with the value. Abbreviations: NA, not available—insufficient space for second sample; ND, not detected; PVC, polyvinyl chloride; THC, tetrahydrocannabinol; THCA, tetrahydrocannabinol acid.

^aAs the 100 cm² template could not be used, an estimated 100 cm² was sampled.

Personal evacuated canister samples, collected side by side with the OSHA method samples, did not detect diacetyl (minimum detectable concentration = 1.2 ppb). Two personal evacuated canister samples (both security personnel) measured trace amounts of 2,3-pentanedione (2.4 and 4.2 ppb) with both samples being between the minimum detectable concentration (2.2 ppb) and minimum quantifiable concentration (10 ppb). Four of six task-based evacuated canister samples (15 minute sample duration) collected during decarboxylation measured diacetyl, but only one sample (21 ppb) was above the minimum quantifiable concentration (7.6 ppb). Two of these task-based samples also measured 2,3-pentanedione (3.9 and 25 ppb) during decarboxylation (minimum quantifiable concentration = 11 ppb). Neither diacetyl nor 2,3-pentanedione was identified in any thermal desorption tube sample.

Full-shift endotoxin concentrations were all below the occupational exposure limit (OEL) of 90 endotoxin units per cubic meter (EU/m³), which is recommended by the Dutch Expert Committee on Occupational Safety.¹⁸ In the United States, OELs for endotoxin have not been established. Personal, full-shift endotoxin air sample concentrations for cultivators were lower (5.4 and 15 EU/m³) on day 1 when compared with day 2 (62 and 85 EU/m³), which differed

only in job tasks by a 45 minute grinding task on day 2. However, these results approached the Dutch recommended OEL.

The internal transcribed spacer region sequencing analysis of the 2016 site visit samples resulted in the identification of 569 sequences, clustered into 137 operational taxonomic units and 806 sequences clustered into 131 operational taxonomic units in samples derived from the 2017 site visit. The phylum Basidiomycota (56%) displayed the highest relative abundance in personal and area samples during the first site visit and the Agaricomycetes (30%) and Wallemiomycetes (22%) were the most prevalent fungal classes (Figure 2A). The phylum Ascomycota were also prevalent in samples accounting for 31% of identified sequences, and primarily consisted of fungi from the class Dothideomycetes (26%; Figure 2A). For sampling in April 2017, there was a shift in the predominant fungal taxa and the classes Cystobasidiomycetes, Ustilaginomycetes, and Wallemiomycetes were not identified during the second visit (Figure 2C). The most common taxa identified in 2016 included *Wallemia* spp, (22%), *Epicoccum nigrum* (8%), *Ganoderma applanatum* (7%), *Cladosporium cladosporioides* (7%), and *Cladosporium sphaerospermum* (5%) (Figure 2B), while in April 2017, the most common taxa were *Irpex lacteus* (10%), *Bjerkandera adusta* (7%), and *Cerrena unicolor* (3%) (Figure 2D). There was a shift in the dominant fungal classes in

TABLE 2 Summary area diacetyl and 2,3-pentanedione environmental air sample results in parts per billion

Location/job title	Samples, n	Sample time, min	Diacetyl	2,3-pentanedione
2016 Evacuated canister method				
Decarboxylation	1	Instantaneous	23	[4.4]
Decarboxylation	4	15	[1.2]-6.7	ND-[1.7]
Grinding	2	15	[0.71.5]	ND
Greenhouse A	1	15	[3.0]	ND
Greenhouse A	2	360-480	[1.6]-4.7	ND-[2.8]
Greenhouse B	2	360-480	3.0-3.7	ND
Vegetation room	1	15	5.8	5.1
Vegetation room	2	360-480	2.7-3.3	ND-[1.3]
Loading dock	2	360-480	[1.9]-12	ND-9.3
Outside grow	2	360-480	[1.6]-[2.1]	ND
2017 OSHA method				
Grinding Room	1	345	ND	ND
Breezeway 1	2	298-373	ND	ND
Breezeway 2	2	338-375	ND	ND
Decarboxylation	2	550-561	ND-[0.26]	ND
NIOSH 8-h time weighted average REL				
			5.0	9.3

Note: Values in brackets are between the minimum detectable concentrations and minimum quantifiable concentrations corresponding to more uncertainty associated with the value.

Abbreviations: ND, none detected; NIOSH, National Institute for Occupational Safety and Health; OSHA, Occupational Safety and Health Administration; REL, recommended exposure limit.

personal and area samples. Wallemiomycetes had a higher abundance in personal air samples (38%), while Agaricomycetes was higher in area samples (49%; Figure 2A).

Plant-derived sequences were also identified and accounted for 37% of all second site visit sequences and included *Cannabis sativa* and other regionally prevalent plant species (Figure 2D). Plant sequences primarily derived from *Cannabis sativa* were also identified and accounted for 80% of all sequences identified in personal air samples.

4 | DISCUSSION

Despite the majority of the facility's production area working with raw cannabis where one would expect to have higher concentrations of the unconverted phytocannabinoid $\Delta 9$ -THCA than $\Delta 9$ -THC, 15 out of 18 (83%) $\Delta 9$ -THC only method samples had detectable concentrations of $\Delta 9$ -THC. Even though not directly comparable because sampling was conducted side-by-side, the $\Delta 9$ -THC only method detected $\Delta 9$ -THC in all but one sample that the four cannabinoid sample detected $\Delta 9$ -THC or $\Delta 9$ -THCA. In contrast, there were six paired samples where the four cannabinoid method did not detect any cannabinoid levels whereas the corresponding $\Delta 9$ -THC only method had detectable levels of $\Delta 9$ -THC. Because raw cannabis contains $\Delta 9$ -THC and the $\Delta 9$ -THC only method has a much lower limit of detection compared with the four cannabinoid method, these results suggest that the $\Delta 9$ -THC only method can be an effective screening tool used in the cannabis industry to identify contaminated areas. These results also support the use of personal protective equipment, such as gloves, when handling cannabis or

working in a cannabis cultivation/processing area, as well as practice of good personal hygiene and the introduction of cleaning schedules to reduce accumulation and exposure of workers to THC.

Even though the surface wipe samples for $\Delta 9$ -THC only and the surface wipes for analysis of four cannabinoids were collected adjacent to one another, equal distribution of cannabinoids across both wipe sample areas cannot be assumed and therefore results cannot be compared directly. However, a comparison can be made for the results within the multiple cannabinoid method. For samples with detectable concentrations using the four cannabinoid method, $\Delta 9$ -THCA concentrations were higher than $\Delta 9$ -THC for every surface wipe sample except for one sample collected near the decarboxylation oven. These results suggest that $\Delta 9$ -THCA surface contamination is greater than $\Delta 9$ -THC when working with raw cannabis. The only sample in contradiction to this trend was collected near the decarboxylation oven. The oven converts $\Delta 9$ -THCA into $\Delta 9$ -THC, which may explain the higher $\Delta 9$ -THC in this sample. Surface wipe samples detected cannabidiol and cannabinol less frequently than $\Delta 9$ -THCA and $\Delta 9$ -THC which may be an artifact of the cannabis strains being processed during sampling or an inability of the sampling method to detect cannabidiol and cannabinol at low levels.

Research is limited on negative health outcomes associated with direct skin contact with $\Delta 9$ -THC or $\Delta 9$ -THCA, as prior studies have primarily evaluated effects from inhalational exposures.¹⁹ Some studies have associated chronic exposure to first hand cannabis smoke with social anxiety disorder, depressive disorders, psychosis, and respiratory symptoms.¹⁹

During the study, a "partially validated" evacuated canister sampling method was used to screen for VOCs, and in August

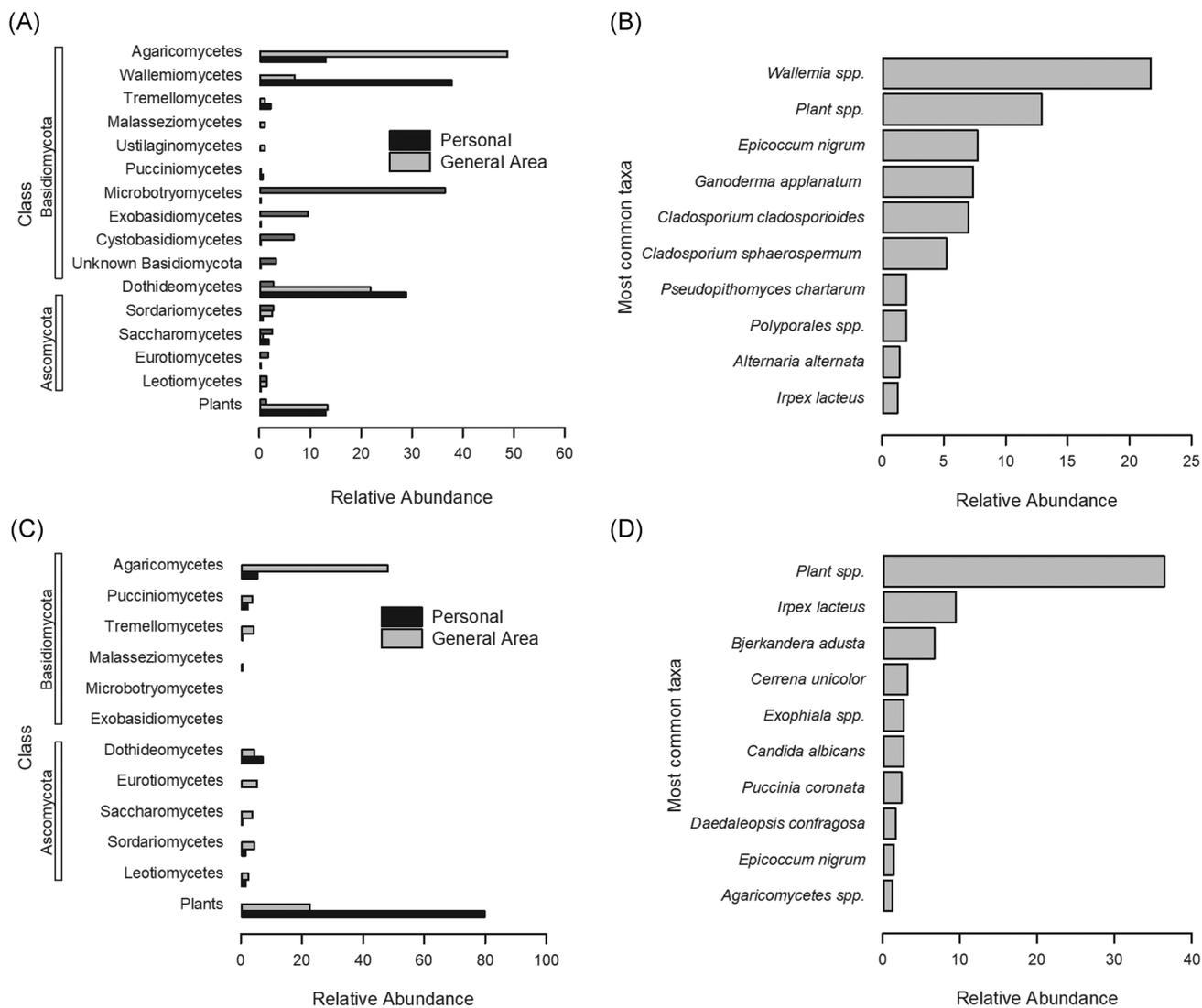


FIGURE 2 Fungal relative abundance by class and sample type (A), and most common fungal taxa (B) for the August 2016 site visit and class and sample type (C), and most common fungal taxa (D) for the April 2017 site visit

2018, the evacuated canister sampling method became a fully validated method.^{11,15} VOC screening was performed in both 2016 and 2017 and due to the detection of the potentially hazardous chemicals (diacetyl and 2,3-pentanedione), a more rigorous follow-up sampling was undertaken in 2017 using the paired evacuated canister and OSHA method sampling (1013 and 1016). While the evacuated canister method yielded higher diacetyl and 2,3-pentanedione concentrations when compared with the corresponding OSHA method concentrations, the OSHA method is the standard regulatory method. For this reason, recommendations were based on the OSHA method results which were all below the NIOSH REL, as well as the short-term exposure limit of 25 ppb for diacetyl and 31 ppb for 2,3-pentanedione.¹⁷ The highest detected level for diacetyl (21 and 23 ppb) and 2,3-pentanedione (25 ppb) were all observed by the evacuated canister method during decarboxylation tasks indicating that decarboxylation is the main source of the chemicals. The OSHA method results for all three cultivators were between the minimum detectable concentration and the minimum quantifiable

concentration. This confirms that diacetyl was present but at low concentrations. These concentrations were at or near the analytical limits of the respective sampling methods which may explain the variable results for both diacetyl and 2,3-pentanedione.

Diacetyl and its substitute, 2,3-pentanedione, are widely used in the flavoring industry. Exposure to these chemicals has been shown to cause decreased lung function and serious respiratory disease, including obliterative bronchiolitis.¹⁷ Obliterative bronchiolitis, also known as bronchiolitis obliterans, is an irreversible lung disease characterized by scarring in the bronchioles. Occupational exposures to airborne diacetyl and 2,3-pentanedione have also been identified in other industries. Bailey et al identified six employees in a coffee processing facility with suspect obliterative bronchiolitis and five employees with work-related asthma associated with high exposures to diacetyl and 2,3-pentanedione.²⁰ Further characterization of potential exposure to these chemicals in cannabis processing facilities is warranted to prevent potential adverse respiratory outcomes.

Exposure to organic dust and high concentrations of endotoxin cause respiratory inflammation, respiratory symptoms, and declines in lung function.²¹ There is variable evidence about the health effects associated with exposure to low endotoxin concentrations (less than 100 EU/m³) but it has been reported that levels as low as 45 EU/m³ may cause acute airflow obstruction, mucous membrane irritation, chest tightness, cough, shortness of breath, fever, and wheezing.²² In this evaluation, endotoxin levels spiked during a short grinding task. As the cannabis industry continues to expand, the scale of these grinding operations may increase, resulting in higher concentration exposures to organic dust and endotoxin. Some studies have suggested that high endotoxin exposures may protect individuals from atopic sensitization.²³ Workers in the hemp industry, an industry thought to have similar exposures to the cannabis industry, have been shown to be exposed to endotoxin concentrations that exceed the Dutch OEL of 90 EU/m³.¹⁸ In one study, Fishwick et al²⁴ showed that the mean levels of inhalable endotoxin in the breathing zone of hemp fiber production workers were substantially higher than the Dutch OEL. Work-related tasks such as sweeping were work practices that resulted in the highest concentrations of endotoxin.²⁵ Hemp dust exposure has also been shown in previous European studies to result in work-related respiratory symptoms in hemp workers including abnormalities of lung function, chronic cough, dyspnea, byssinosis, as well as an increased incidence of skin test reactivity to hemp extracts.²⁵⁻²⁹

Internal transcribed spacer region sequencing revealed fungal taxa commonly detected in occupational environments.³⁰ Basidiomycota and Agaricomycetes were the most frequently identified fungal sequences in general area samples collected at the Minnesota facility, accounting for 20% of all fungal sequences. This includes Basidiomycota genera that form basidiocarps (eg, mushrooms) that break down wood.³¹ Agaricomycetes was the most prevalent fungal class captured in a recent survey of a cannabis facility in the state of Washington.⁶ In contrast, personal air sampling of workers conducting harvesting and processing tasks was dominated by the Basidiomycota genus *Wallemia*. Previous studies that have assessed exposure to fungi during cannabis processing or harvesting applications have identified the cannabis plant pathogen *Botrytis cinerea*.⁶ In this evaluation, *Botrytis cinerea* only accounted for 0.72% and 1.04% of fungal sequences identified during the first and second site visits, respectively.

Similar to this evaluation, other studies utilizing next generation sequencing have characterized the cannabis mycobiome that includes a variety of pathogenic and toxigenic *Aspergillus* and *Penicillium* species.^{32,33} The results derived from the current study suggest that *Wallemia* species were either growing on processed cannabis or were present in the general vicinity of the worker. *Wallemia* is a common fungal contaminant in damp indoor and agricultural environments and personal exposure has been associated with respiratory morbidity such as hypersensitivity pneumonitis.^{34,35} Additional analysis of cannabis processing environments in varying geographical environments is needed to provide a better understanding of fungal communities that workers could be exposed to during harvesting and processing activities.

We believe that this study adds valuable information to the literature with regard to potential occupational hazards related to cannabis but does have limitations that should be addressed in future research. Since a direct comparison between the two surface sampling methods could not be made, this study highlighted that care must be taken when selecting surface sampling methodology and that each method's advantages and disadvantages should be considered when designing exposure assessment protocols. Additionally, while traditional industrial hygiene exposure assessments deal with chemical measurements and OELs in the parts per million range, diacetyl and 2,3-pentanedione limits are measured and compared against OELs in the low ppb range. Characterizing exposures at these low ppb levels, which approach the analytical limits of detection, poses special exposure assessment challenges.

5 | CONCLUSIONS

To the authors' knowledge, this is the first published report of potential diacetyl and 2,3-pentanedione exposure in the cannabis industry, most notably during cannabis decarboxylation, albeit at levels significantly below the NIOSH REL and action level. Endotoxin exposure was elevated during grinding, indicating that this is a potentially high risk task. The results for fungal exposures, including the high relative abundance of the Basidiomycota genus *Wallemia*, indicate that bioaerosol exposure should also be considered when characterizing health hazards at cannabis operations, or when medically evaluating persons that work in the cannabis industry. Considering results were collected at only one facility, further investigation is needed to better characterize the presence and concentrations of diacetyl and 2,3-pentanedione across this emerging industry.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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AUTHOR CONTRIBUTIONS

Each author, including James R. Couch, PhD, George R. Grimes, MD, Douglas M. Wiegand, PhD, Brett J. Green, PhD, Eric K. Glassford, MS, Leonard M. Zwack, ScD, Angela R. Lemons, MS, Stephen R. Jackson, PhD, Donald H. Beezhold, PhD, participated in the conception or design of the work; the acquisition, analysis, or interpretation of data for the work; drafting the work or revising it critically for important intellectual content; final approval of the version to be published; and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

ETHICS APPROVAL AND INFORMED CONSENT

The following language is included in the Section 2 of this paper: Health Hazard Evaluations are not considered human subjects research by virtue of NIOSH acting as a public health authority performing a public health investigation as directed by statute. Participants were informed of the purpose of the evaluation, their rights regarding confidentiality, and the voluntary nature of participation. Informed consent was provided verbally.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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