

Measurement of diacetyl and related compounds in coffee roasteries and breweries

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ABSTRACT

α -Diketones such as diacetyl (2,3-butanedione) and 2,3-pentanedione are generated during the roasting and fermentation of foods and are also used as flavoring compounds. Exposure to these compounds has been associated with *obliterative bronchiolitis* in workers. We report indoor air concentrations of diacetyl and 2,3-pentanedione, as well as acetoin (3-hydroxy-2-butanone), in several small coffee roasteries and breweries using standard integrated air sampling sorbent tubes followed by GC-MS/MS as well as the first use of on-site continuous real-time proton transfer reaction mass spectrometry (PTR-ToF-MS). Diacetyl and 2,3-pentanedione were detected in most of the sorbent samples at concentrations between 0.02 to 8 ppb_v, and in general were higher in coffee roasteries compared to breweries. Three integrated air samples, all from the barista area at one facility, exceeded the NIOSH recommended exposure limit (REL) of 5 ppb_v for diacetyl. 2,3-pentanedione concentrations in these three samples were greater than 50% of its REL, but did not exceed it. Acetoin, a precursor to diacetyl, was also detected at concentrations between 0.03 to 5 ppb_v in most sorbent tube samples, with concentrations generally higher in breweries. PTR-ToF-MS measurements exhibited similar trends and provided continuous real-time VOC data that showed episodic excursions with peak concentrations of diacetyl and 2,3-pentanedione between 15 – 20 ppb_v.

Examination of the time series data identified specific activities associated with peak diketone emissions, including transfer of freshly roasted coffee beans to the cooling tray, or the opening of a brew kettle. Additional indoor air quality parameters including CO₂, NO₂, and PM_{2.5} were also assessed on-site. Airway inflammation was assessed in 19 workers before and after each work shift using on-line measurements of fractional exhaled nitric oxide (F_ENO). The pre-shift mean F_ENO was 3.7 [95% confidence interval: -3.6, 11.0] ppb_v higher and the post shift F_ENO was 7.1 [-1.9, 16.1] ppb_v higher for workers at coffee roasteries compared to breweries. The cross-shift change in F_ENO was 3.4 [-2.8, 9.6] ppb_v higher for workers at coffee roasteries compared to breweries. However, none of these differences were statistically significant,

45 and the cross shift change in F_ENO was not statistically different from zero for either group of workers. The
46 findings from this pilot study demonstrate that α -diketones and related compounds are present in the indoor
47 air of both breweries and coffee roasteries and may exceed health protective guidelines in coffee roasteries.
48 Additional studies are required to fully characterize worker exposures in these settings, and to identify
49 specific work activities and processes associated with high exposures. Engineering controls, including
50 targeted exhaust ventilation and the use of low-cost sensors are recommended as an approach to protect
51 workers from exposure to hazardous levels of α -diketones.

53 INTRODUCTION

54 Diacetyl and related α -diketones, such as 2,3-pentanedione, are added to food products as natural
55 and artificial flavoring agents that impart a buttery taste and aroma (NIOSH, 2016). They are also present as
56 natural byproducts in some fermented food products including cheese, yogurt, miso, and beer (Ott et al.,
57 1999, Frank et al., 2006, Giri et al., 2010, NIOSH, 2016), and in roasted food products such as coffee (Duling
58 et al., 2016). Inhalation exposure to diacetyl and 2,3-pentanedione is associated with respiratory disease
59 including *obliterative bronchiolitis* (Bailey et al., 2015), a severe, irreversible lung disease characterized by
60 fixed airways obstruction.
61

62 In the early 2000s, cases of *obliterative bronchiolitis* were identified in diacetyl-exposed workers
63 from a diacetyl manufacturing plant, several microwave popcorn manufacturing facilities (NIOSH, 2016),
64 and in coffee processing facilities (Bailey et al., 2015, NIOSH, 2016, Harvey et al., 2021). Table 1 summarizes
65 the 8-hour time weighted average (TWA) and short-term exposure limit (STEL) from the American
66 Conference of Governmental Industrial Hygienists (ACGIH), the European Commission, and the US National
67 Institute for Occupational Safety and Health (NIOSH). The US Occupational Safety and Health Administration
68 (OSHA) does not currently have a permissible exposure limit (PEL) for these compounds. Although much

69 research has focused on diacetyl-exposed workers in the food and flavor industry (Parmet and Von Essen,
70 2002, Kreiss et al., 2002, Kanwal et al., 2006, Akpinar-Elci et al., 2004), fewer studies have focused on small
71 coffee roasteries and breweries. There are several recent publications that demonstrate coffee worker
72 exposures to diacetyl and pentanedione in exceedance of the NIOSH RELs. In general, coffee grinding
73 activities have been observed to give rise to higher concentrations than roasting. For example, the TWA 8-hr
74 diacetyl concentrations associated with coffee roasting and grinding were reported as 6.4 and 9.4 ppb_v,
75 respectively (McCoy et al., 2017). The results of several studies are summarized in recent reviews of the
76 literature (LeBouf et al., 2020, Echt et al., 2021).

77 *Table 1: Recommended time weighted and short-term exposure limits for diacetyl.*

	ACGIH		EC		NIOSH	
	TWA 8-hr	STEL 15 min	TWA 8-hr	STEL 15 min	TWA 8-hr	STEL 15 min
diacetyl	10 ppb _v	20 ppb _v	20 ppb _v	100 ppb _v	5 ppb _v	25 ppb _v
2,3-pentandione	-	-	-	-	9.3 ppb _v	31 ppb _v

78

79 Both integrated and continuous (direct reading) air sampling methods are common for measuring
80 indoor and outdoor air. The two methods can provide complementary data sets (Davey et al., 2020), both of
81 which have unique advantages and disadvantages. For example, integrated sampling that uses a sorbent tube
82 combined with GC-MS analysis (LeBouf and Simmons, 2017) is both sensitive and selective providing
83 quantitative measurements of individual VOCs on discrete samples. Continuous monitoring of VOCs using
84 PTR-ToF-MS (Yuan et al., 2017, Warneke et al., 2011) provides sensitive (ppt_v) and mass selective
85 measurements with frequencies as high as 1 Hz. These time-resolved measurements provide unique insights
86 on the impact of specific activities and/or engineering control systems that mitigate exposure. However,
87 PTR-ToF-MS methods are generally less selective than GC-MS/MS methods, as structural isomers will appear
88 at the same mass/charge ratio and are therefore not distinguished.

89 The objective of this pilot study is to use PTR-ToF-MS to continuously measure the concentrations of
90 α -diketones and a known diacetyl precursor (acetoin) in several small coffee and beer processing facilities.
91 These compounds were simultaneously measured over the course of the workday to identify short-term
92 concentration excursions and their relationship to specific activities. Simultaneously, we collected integrated
93 samples over an intermittent 8-hr period as well as a continuous 1-hr period on sorbent tubes at several
94 locations within these facilities for off-line analysis following OSHA methodology (OSHA-1013, OSHA-1016).
95 We also present data for auxiliary indoor air quality including methane, carbon dioxide, nitrogen oxides, and
96 fine particulate matter (PM_{2.5}). Finally, workers were recruited to participate in exhaled breath monitoring
97 for fractional exhaled nitric oxide (F_ENO), which is a marker of airway inflammation.

98 METHODS

99 100 **Method of workplace recruitment**

101
102 Several craft coffee roasting and brewing business owners on Vancouver Island, BC, Canada were
103 approached in person, via email, or through phone contacts. Participating facilities were selected based on
104 location, size of operation, and interest level of owners/operators. Two coffee roasters (CR#1 and CR#2) and
105 two breweries (BR#1 and BR#2) were selected to participate in the study. Details about the facilities (size,
106 layout, sampling strategy, and number of employees) can be found in the supplementary information (Table
107 S1 and Figures S1 – S8).

108 109 **Study subjects**

110 Workers were recruited from each of the facilities to participate in exhaled breath monitoring for
111 fractional exhaled nitric oxide (F_ENO). Several days prior to the dates of sample collection, a one-page
112 summary document describing the research study was sent to facility managers, who forwarded this
113 information to their workers. On the morning of sample collection, workers who wished to participate in the

114 exhaled breath sampling met with the research study coordinator and completed a consent form to
115 participate in the study. The study procedures were reviewed and approved by the University of Washington
116 Institutional review board (IRB ID: STUDY00002320). Between one and seven workers from each facility
117 participated in the exhaled breath monitoring. $F_{E}NO$ measurements were obtained from each subject
118 immediately before they started the work-shift, and again at the end of the work shift. For two of the
119 facilities, $F_{E}NO$ measurements were obtained before and after two work shifts, whereas at the other two
120 facilities only one pair of $F_{E}NO$ measurements was obtained per worker.

122 **Exhaled breath monitoring**

123 Airway inflammation was assessed by measurements of $F_{E}NO$ using a portable chemiluminescence
124 analyzer (NIOX VERO; Morrisville, NC, USA), according to manufacturer instructions. Quality control
125 procedures were completed as specified by the manufacturer, which included (i) verification of instrument
126 zero response consisting of a NO free gas sample automatically generated from ambient air, and (ii) daily
127 measurement of a positive control from one member of the research team with a stable $F_{E}NO$ value within
128 the normal biological range. In addition, subjects were instructed to avoid strenuous exercise or eating
129 nitrate rich foods during the three hours prior to $F_{E}NO$ measurement.

131 **Air sampling**

132 We used two complimentary methods to measure diacetyl, 2,3-pentanedione, 2,3-hexanedione, 2,3-
133 heptanedione, and acetoin in indoor air. The first method utilized sorbent tube samplers with subsequent gas
134 chromatography tandem mass spectrometry (GC-MS/MS) analysis to measure time-integrated air
135 concentrations. The second method employed was proton-transfer reaction time-of-flight mass spectrometry
136 (PTR-ToF-MS), which allows for direct continuous measurement for compounds of interest.

138 **Sorbent tube sampling method**

139 Full-shift 8-hr time-weighted average (TWA) samples, designed to represent work shift average
140 exposure, were collected at 2 – 4 locations within each facility. The locations were selected based on
141 proximity to different tasks or activities within the facility. In addition, several 45 – 51 minute short-term
142 exposure samples were collected at each facility in conjunction with specific activities. For 8-hr TWA samples
143 the pump was programmed to sample intermittently for one minute in every five minutes across 8 hours, to
144 avoid breakthrough of the analyte on the sorbent tubes. For the short-term samples, designed to capture
145 specific work activities, the pump operated continuously. These area samples allow for comparison of the
146 standard sorbent tube method with the PTR-ToF-MS but do not represent the personal exposure of each
147 employee. As such, exposure limits provide a benchmark against which the area samples may be compared,
148 but the area samples do not represent actual exposures. Sample volumes ranged from 7.6 – 8.8 L for the
149 short-term samples, and from 6.9 – 9.4 L for the TWA samples.

150 Sampling for the target analytes diacetyl, acetoin (3-hydroxy-2-butanone), 2,3-pentanedione and 2,3-
151 hexanedione was undertaken using two pre-cleaned silica gel sorbent tubes (7×110-mm, 600 mg, Cat. No.
152 226-183, SKC Inc., Eighty Four, PA) connected in series, as specified in OSHA 1012 (OSHA-1012) and OSHA
153 1016 (OSHA-1016). Air was drawn through the tubes using battery powered personal sampling pumps (PCXR,
154 SKC Inc.) connected to the sorbent tubes via an adjustable low flow tube holder (SKC, Inc.), at a nominal flow
155 rate of either 100 mL/min (TWA samples), or 200 mL/min (short-term exposure samples). Flow rates were set
156 and verified in the field using a calibrated rotameter (SKC Inc., Eighty Four, PA). Sorbent tubes were
157 protected from light by wrapping with aluminum foil. Immediately after collection, samples were stored on
158 ice in the field, and transferred to a refrigerator at the end of each workday.

159

160 Sorbent tube analysis method

161 Three α -diketones and acetoin were measured by a gas chromatograph-mass spectrometer (GC-
162 MS/MS) method, with some modifications (OSHA-1013, OSHA-1016, LeBouf and Simmons, 2017, Echt et al.,
163 2021). Sorbent material was removed from the glass tubes then extracted in 2 mL of 5% methanol/acetone
164 spiked with internal standards diacetyl- d^6 and 2,3-pentanedione-1,1,1,4,4- d^5 . The GC-MS/MS system (Agilent
165 7890B/7000, Santa Clara, CA) used for analysis was operated in multiple reaction monitoring (MRM) mode
166 with precursor and product ion transitions appropriate for qualitative and quantitative determination (Table
167 S2). Samples were analyzed in two batches, each within 17 days of sample collection (OSHA-1013, OSHA-
168 1016). Mid-range calibration verification standards were analyzed throughout each batch (> 1:20 injections),
169 with acceptable recoveries for all compounds (77 – 103%). Assay contamination was assessed using
170 laboratory and field blanks (sorbent tubes through which no air was drawn). Low levels of all four analytes
171 were detected in laboratory blanks, ranging between 0.001 ng/sample (2,3-hexanedione) to 1.75 ng/sample
172 (diacetyl). Analyte levels in the field blank samples were not significantly different from the levels in the
173 laboratory blanks. Therefore, sample concentrations were corrected by subtracting the average of the
174 laboratory blanks. Minimum detection limits (MDL) ranged from 1 ng/sample (2,3-hexanedione) to 2
175 ng/sample (diacetyl) and determined as the greater of the lowest calibration standard (after blank
176 subtraction) or the laboratory blank. This MDL is equivalent to an air concentration of approximately 0.02 –
177 0.06 ppb_v assuming a 10 L air sample.

178 Real-time Measurements

179 The Mobile Mass Spectrometer Lab (MMSL) housed in a research purposed Mercedes-Benz Sprinter
180 van was equipped with a proton transfer reaction time-of-flight mass spectrometer (PTR-ToF-MS, Ionicon
181 PTR-TOF1000, IONICON Analytik, Innsbruck, Austria), an NO_x analyzer (model 42i, ThermoFisher), and a fast
182 greenhouse gas analyzer (FGGA 30r, Los Gatos) for CO₂, CH₄ and H₂O was parked with the engine off within
183 3m of an outside entryway to each sampling site and plugged in to building power. These instruments

184 operate continuously and provide parallel time series data collected at 0.1 – 1 Hz. Fluorinated ethylene
185 propylene (FEP, Cole Parmer) tubing with ¼" outer diameter (OD) was used for NO_x and greenhouse gas
186 analysis. Sample lines were typically between 10 – 30 m in length depending on the proximity to the
187 designated sampling point. The NO_x analyzer was calibrated by the vendor (CD Nova Ltd) immediately prior
188 to deployment. The greenhouse gas analyzer was not calibrated immediately prior to deployment but
189 reported ambient outdoor concentrations of 410 – 420 ppm_v and 1.8 – 1.9 ppm_v for CO₂ and CH₄,
190 respectively, consistent with government agency reported values for these well mixed gases. An Optical
191 Particle Sizer (model 3330, TSI Inc., Shoreview, MN, USA) was employed inside each facility to count and size
192 particles between 0.3 – 10 µm at 1 second intervals. PM_{2.5} was calculated by summing particle size bins up to
193 2.5 µm diameter and reported in µg/m³ using vendor algorithm. Ambient outdoor conditions (relative
194 humidity, pressure, and temperature) were recorded with an on-board weather station (Model 597, MetOne
195 Instruments Inc., Grants Pass, OR USA) during sampling trips.

196 VOCs were continuously sampled using perfluoroalkoxy alkane (PFA) tubing (¼" OD) insulated with
197 foam pipe wrap and connected to the PTR-ToF-MS. A dedicated pump (Model DOA-P704-AA, GAST
198 Manufacturing, Inc., MI USA) was used to pull sample air into the vehicle (~ 20 L/min), which was subsampled
199 by the PTR-ToF-MS at 0.75 L/min resulting in a sample transport time of approximately 7 – 13 seconds,
200 depending on the location. PTR-ToF-MS measurements were made at 1 Hz and minimum detection limits
201 (MDL; ppb_v) were defined as the concentration which had an average signal three times greater than the
202 standard deviation of a blank, after background subtraction. The MDL for diacetyl was 0.3 ppb_v and for 2,3-
203 pentanedione was 0.6 ppb_v. Although some progress has been made by others to differentiate
204 isobars/isomers with PTR-ToF-MS (Shen et al., 2012), no effort was made to do so here. As such, time
205 resolved VOC concentrations reported should be considered semi-quantitative due to potential interference
206 from compounds with similar or identical m/z . The mass resolution ($m/z/\Delta m/z$) ranged from 1500 – 2000 at

207 *m/z* 59. Calibrations are shown in Figure S9, and a list of the target analytes and potential isobars/isomers is
208 presented in Table S3.

209 A direct comparison between PTR-ToF-MS and GC-MS/MS proved challenging due to differences in
210 the sampling methods, the time scale of the measurements themselves, and difficulties in constructing a
211 well-mixed air standard. The RSD for the replicate constructed air samples were 4.3% and 20% for the PTR-
212 ToF-MS and GC-MS/MS analysis, respectively (Table S4). There is good correlation between the two sets of
213 measurements, with a R^2 of 0.88 for diacetyl and a R^2 of 0.84 for pentanedione for co-located samples across
214 all facilities (Figure S10). In general, the PTR-ToF-MS values were higher (~30%) than the co-located sorbent
215 tube concentrations in the field measurements. This positive bias may have resulted from the presence of
216 VOCs with the same *m/z* as the target analytes.

218 RESULTS

219 The results of a total of eight on-site sampling days at coffee and brewery locations revealed indoor
220 air concentrations of α -diketones above the minimum detection limits. Observations were made over three
221 consecutive days at one each of the coffee and brewery locations to capture the full range of operational
222 activities. Diketone levels were observed to be strongly dependent on sampling location and specific
223 activities within the facilities.

225 Sorbent tube measurements

226 The 8-hr sorbent tube measurements are summarized in Table 2, which indicates that diacetyl and
227 2,3-pentanedione were detected in most of the sorbent samples at concentrations between <0.04 – 8 ppb_v.
228 Acetoin was also detected at concentrations between 0.03 – 5 ppb_v in most sorbent tube samples. Figure 1 is
229 a box plot summarizing the sorbent tube results for both the TWA samples and the short-term samples,
230 across the four facilities surveyed in this study. Overall, the TWA levels of these compounds were well below
231

232 occupational exposure guidance values in these facilities, although diacetyl and 2,3-pentandione were
233 observed to be elevated at one of the coffee roasters. Specifically, over the 3-day sampling campaign, the
234 average concentrations near the barista bar at CR#1 were 7.1 and 7.0 ppb_v for diacetyl and 2,3-
235 pentanedione, respectively. A detailed summary of the sorbent tube results is tabulated in the
236 supplementary material (Tables S5 and S6).

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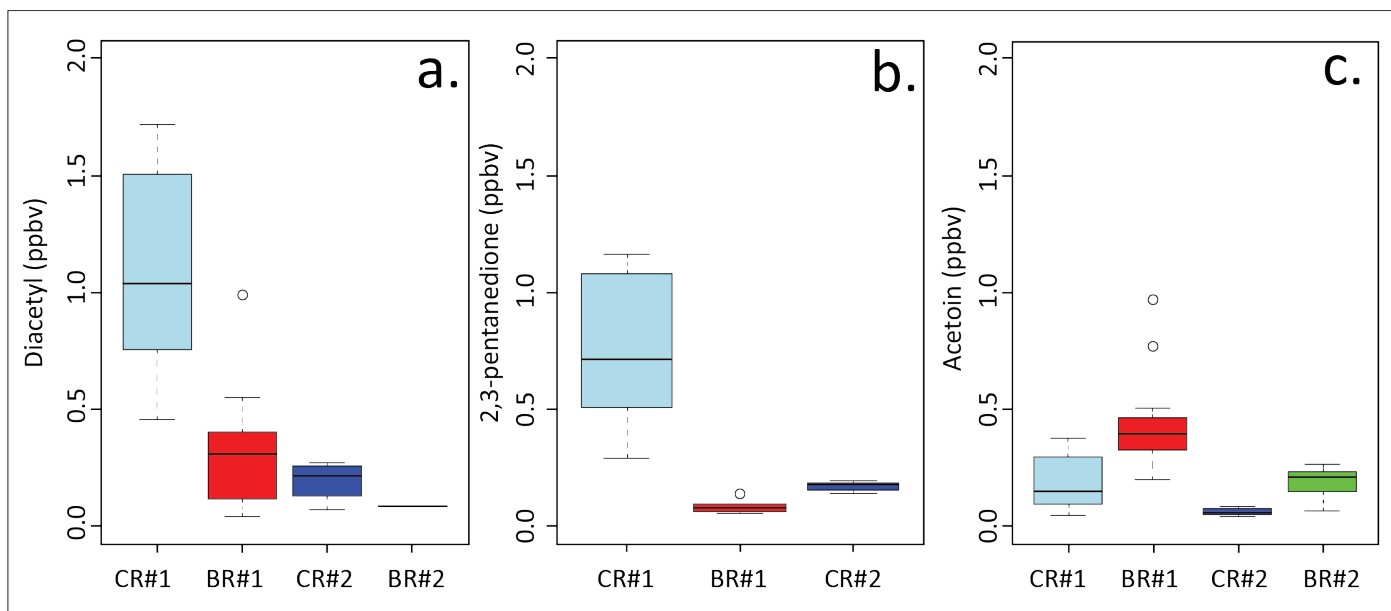
Table 2: Summary sorbent tube measures of diacetyl and related compounds in breweries and coffee roasteries. Concentrations in ppbv.

8-hr TWA	Diacetyl	2,3-pentanedione	Acetoin	2,3-hexanedione
Coffee Roasteries (# samples = 15)				
Fraction>MDL	15/15	15/15	15/15	0/15
Median ^a	0.87	0.63	0.13	-
Mean (SD)	1.06 (2.69) ^b	0.79 (2.72) ^b	0.23 (1.64)	-
Range	0.19 – 7.88	0.14 – 8.01	0.04 – 4.62	-
8-hr TWA	Diacetyl	2,3-pentanedione	Acetoin	2,3-hexanedione
Breweries (# samples = 12)				
Fraction>MDL	10/12	5/12	12/12	0/12
Median ^a	0.28	0.07	0.36	-
Mean (SD)	0.23 (0.28) ^b	0.08 (0.03) ^b	0.34 (0.25)	-
Range	< 0.07 – 0.99	< 0.04 – 0.14	0.06 – 0.97	-

^aOnly samples >MDL included in calculation of mean, median and SD.

^bMeans differ significantly (p=0.05) for brewery vs coffee roaster (based on independent samples t-test).

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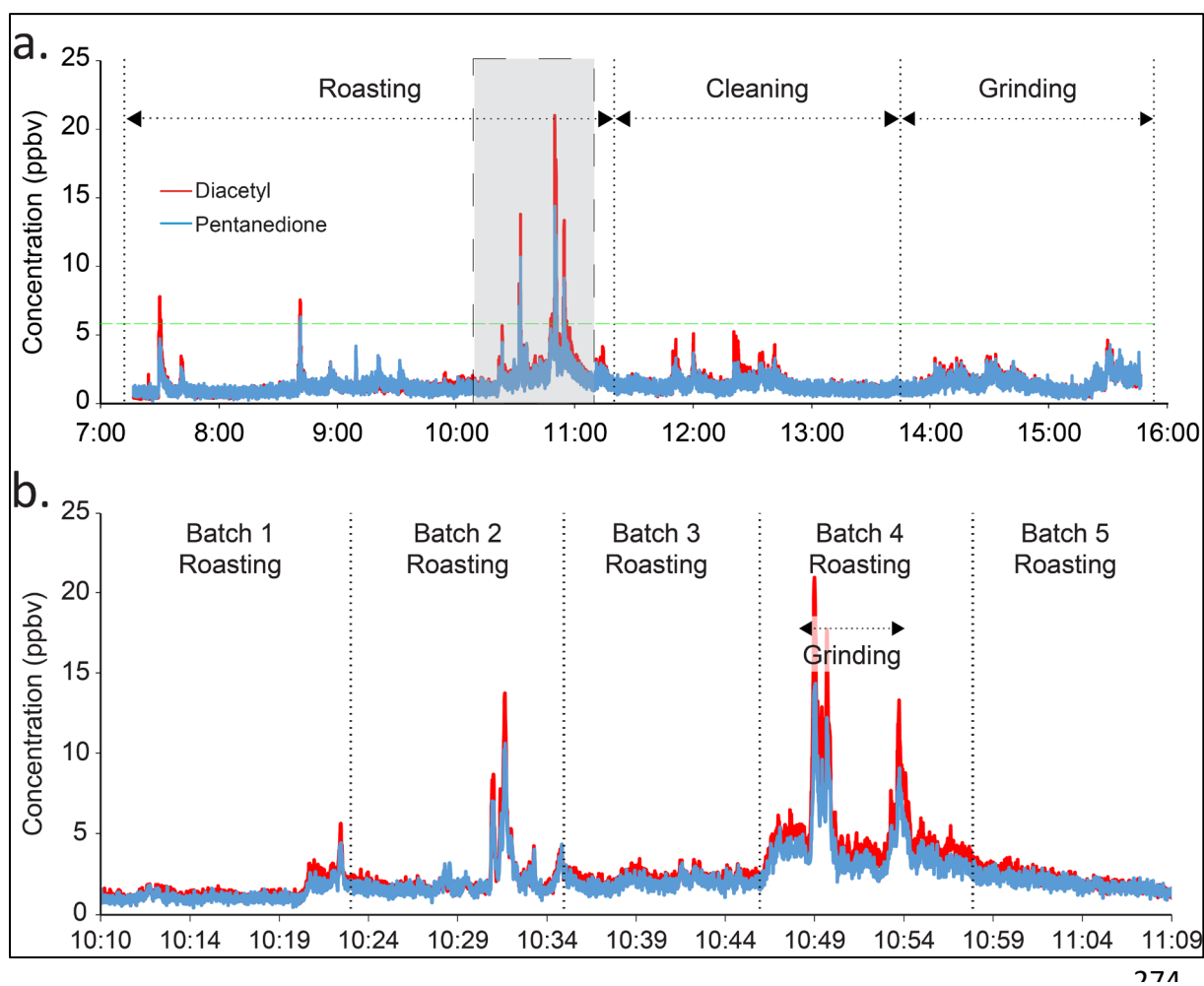
Figure 1: Comparison of (a) diacetyl, (b) 2,3-pentanedione and (c) acetoin concentrations across the four facilities surveyed. 2,3-Hexanedione was only detected in three samples (all at facility CR#1) and hence is not included in these plots. 2,3-pentanedione was not detected at facility BR#2. Data <LOD treated as missing. On each box the central mark indicates the median, the bottom and top edges of the box indicate the 25th and 75th percentiles. Observations above the 95th percentile are plotted using the 'o' symbol. Note that the y-axis is truncated to permit visual comparison across facilities: three diacetyl samples were above 2 ppbv, and are not included here (see Table S5 for all data).

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PTR-ToF-MS measurements

Time series data collected at CR#1 shows diacetyl and 2,3-pentanedione concentrations were highly correlated ($R = 0.84$, Figure S10b) with each other over the 9-hour observation period (Figure 2). The top panel (2a) identifies three broad activity categories as roasting, cleaning, and grinding. During roasting – numerous concentration excursions are evident which generally correspond to when the freshly roasted beans were dumped from the roaster onto cooling trays. During cleaning – the roaster, exhaust vent, and surrounding area was cleaned with brushes or brooms. During grinding – roasted beans from storage containers were ground and packaged in conventional coffee bags with valves. The air inside the facility was not well mixed and the sampling line for continuous measurements was in the center of the facility closer to the roasting than the grinding operations (Figure S2). Figure 2b is an expanded view of the timeseries during the highest concentrations observed between 10 and 11am, during which time operators processed five batches of espresso. Activities during this time included the use of a non-ventilated mini-roaster, roasting and cooling of coffee beans, and grinding of roasted beans.

An example PTR-ToF-MS time series for diacetyl from a brewery (BR#1) is shown in Figure 3. Broad activity categories are identified as: lautering (separating wort from residual mashed grain), boiling, and transfer of wort (the liquid extracted from mashing the grain). One concentration excursion was observed during lautering when the mash tun was temporarily opened (Figure 3 ii). The highest concentration excursions were observed during boiling when the kettle lid was opened for a significant amount of time (~ 1 hour) to prevent overboiling (Figure 3 iv). During transfer, the wort was cooled and pumped to large fermenting tanks. No significant concentration excursions were observed during this stage of the process.



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Figure 2: Timeseries of diacetyl and 2,3-pentanedione concentrations measured at CR#1 on Feb 20, 2018. Top panel is the time series for the whole day, grey shading indicates data shown in the bottom panel. The green dashed line displays the NIOSH time weighted average REL for diacetyl at 5 ppbv. Bottom panel shows a one-hour period when five batches of espresso beans were processed.

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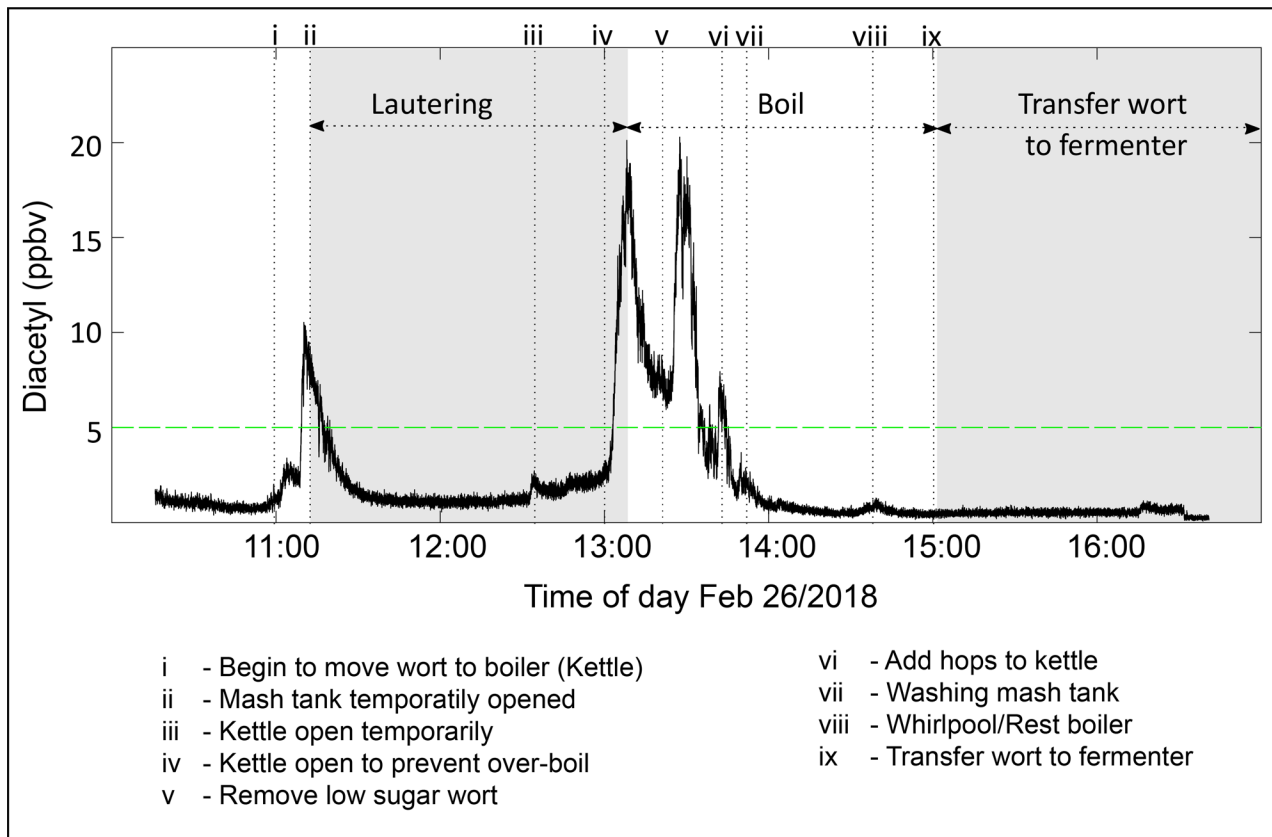
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Continuous α -diketone measurements revealed median concentrations for diacetyl and 2,3-pentanedione were typically below 2 ppbv (Table S5) and summarized in Figure 4. However, it is clear in the time resolved PTR-ToF-MS data that concentration excursions up to 15-20 ppbv can occur in indoor air and that these elevated levels were strongly correlated with specific activities inside the facilities. Diacetyl and pentanedione had measured concentration excursions above the minimum detection limit at each facility on each sampling day.



289
290 Figure 3: Timeseries of diacetyl concentration during brewing at BR #1 on Feb 26, 2018. The green dashed line displays
291 the NIOSH time weighted average REL for diacetyl at 5 ppbv.

292
293 Three full workdays (~8hr/day) of sampling were collected for CR#1 and one full workday of sampling
294 was collected at CR#2. On the first day of sampling at CR#1 (CR#1a) there was no coffee roasting taking place.
295 Both the second (CR#1b) and third (CR#1c) days of sampling had active roasting for approximately 5.5 hr
296 (typically 7:30am – 1pm). The maximum and median concentrations for diacetyl and pentanedione measured
297 at CR#1 were higher on the days of active roasting. The median concentration for diacetyl on roasting days at
298 CR#1 (1.30 ppbv) was twice that of CR#1 on a non-roasting day (0.67 ppbv). Furthermore, the number of
299 observations with diacetyl greater than 5 ppbv was substantially higher on days when roasting occurred.
300 Very similar observations are made for pentanedione with median concentrations of 0.45 ppbv non-roasting
301 day and 1.24 ppbv on days when roasting occurred. During active coffee roasting the median concentration
302 for acetoin at CR#1b was 0.10 ppbv. The second coffee roastery (CR#2) consisted of a single roaster in a

303 building with a high ceiling and modern ventilation. The main activity was roasting and the median diacetyl
304 and pentanedione concentrations were 0.58 ppb_v and 0.81 ppb_v, respectively.

305 Three full workdays (~8hr/day) of sampling were collected for BR#1 and one full workday of sampling
306 was collected at BR#2. The brewing activity at BR#1 was similar on day 1 (BR#1a) and day 3 (BR#1c), with
307 median concentrations for diacetyl of 0.98 and 0.69 ppb_v, respectively. On day 2 (BR#1b) the main activity
308 was canning with minimal brewing activity. The median diacetyl concentration was at or below our detection
309 limit of 0.3 ppb_v on that day. The second brewery (BR#2) was a larger facility (see Table S1 and Figure S5),
310 which did not require opening of the kettles to prevent over-boil as in BR#1. The median diacetyl and
311 pentanedione concentrations were at or below our detection limits at this facility. Hexanediones were
312 generally observed to be below 2 ppb_v, except at the BR#2, where several observations between 2-4 ppb_v
313 were made. Heptanediones were not generally observed in indoor air across this sampling campaign. The
314 maximum and median acetoin concentrations were higher at breweries than coffee roasting facilities. During
315 active brewing, the median concentrations for acetoin at BR#1b (1.42 ppb_v) and BR2#2 (4.37 ppb_v) were an
316 order of magnitude higher than that of CR#1b (0.10 ppb_v).

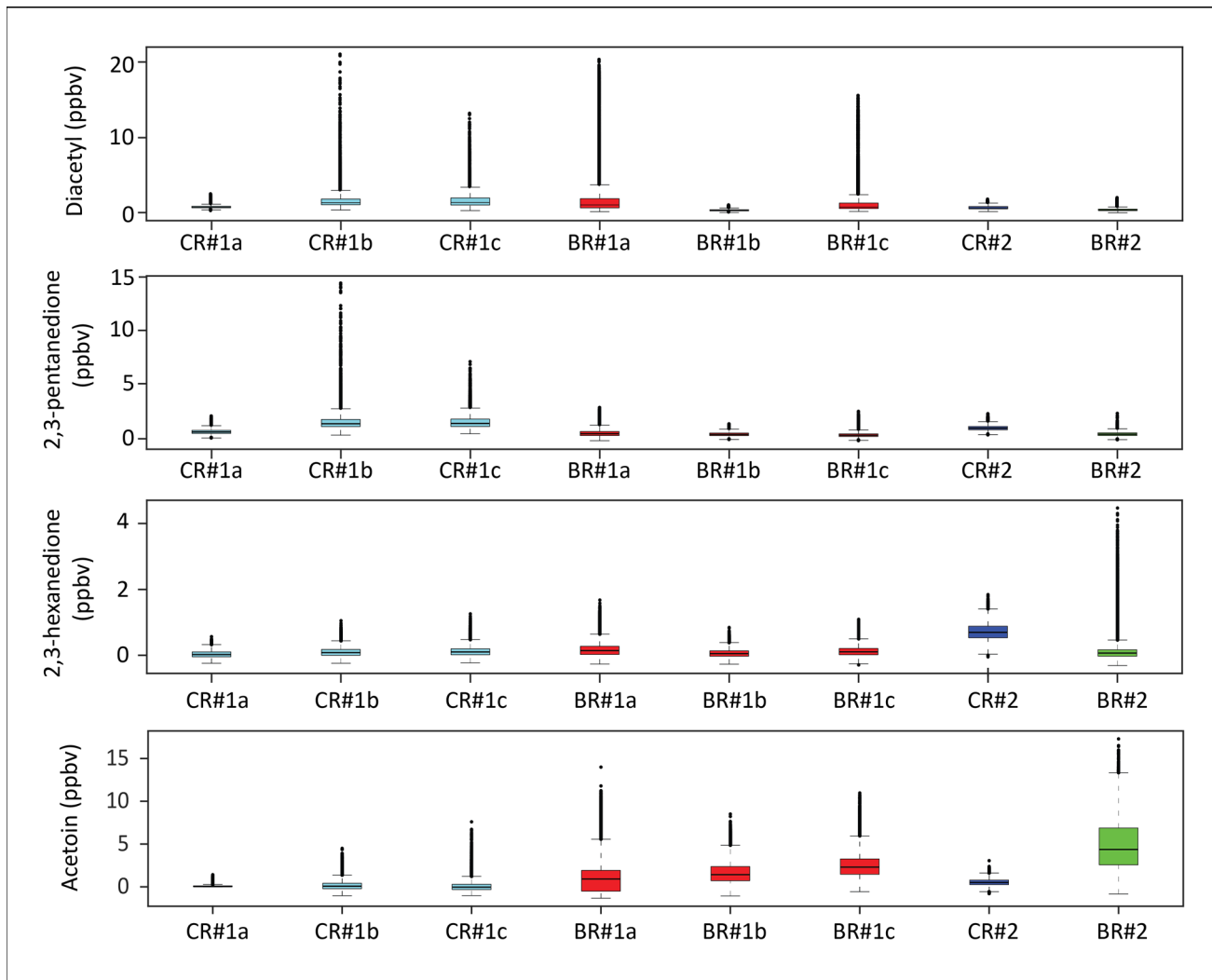


Figure 4: PTR-ToF-MS results for diacetyl, 2,3-pentanedione, 2,3-hexanedione, and acetoin concentrations at breweries and coffee roasteries. On each box the central mark indicates the median, the bottom and top edges of the box indicate the 25th and 75th percentiles. Observations above the 95th percentile are plotted using the 'o' symbol.

320 **Additional indoor air quality measurements**

321 Continuous measurements of NO, NO₂, CH₄, CO₂ and PM_{2.5} were made at all locations over the 8-day
322 sampling period. Summary boxplots are presented in Figure 5 and representative time series are presented in
323 Supplemental Information (Figures S11, S14, S15, S17, S18). Elevated concentrations NO, NO₂, and CH₄ were
324 observed during roasting at CR#1 (CR#1b and CR#1c) but remain well below occupational exposure limits.
325 Elevated PM_{2.5} was observed at CR#1 during roasting, consistent with visually observable smoke released
326 when roasted beans were dumped onto the cooling tray. At CR#1 the 8-hr TWA PM_{2.5} concentrations,
327 measured on two separate roasting days, were 30 µg/m³ and 31 µg/m³. An example time series showing co-
328 incident periodic concentration fluctuations for PM_{2.5} and diacetyl is shown in Figure S11. At the brewery
329 BR#1, elevated CO₂ concentrations (median = 432 ppm_v, max = 4614 ppm_v) were observed during the day
330 when canning was the main activity (BR#1b). At the brewery BR#2, elevated CO₂ concentrations were also
331 observed (median = 448 ppm_v, max = 6866 ppm_v) but could not be attributed to a specific activity. While
332 individual observations occurred above 5000 ppm_v, none of the CO₂ measurements exceeded TWA or STEL
333 exposure limits.

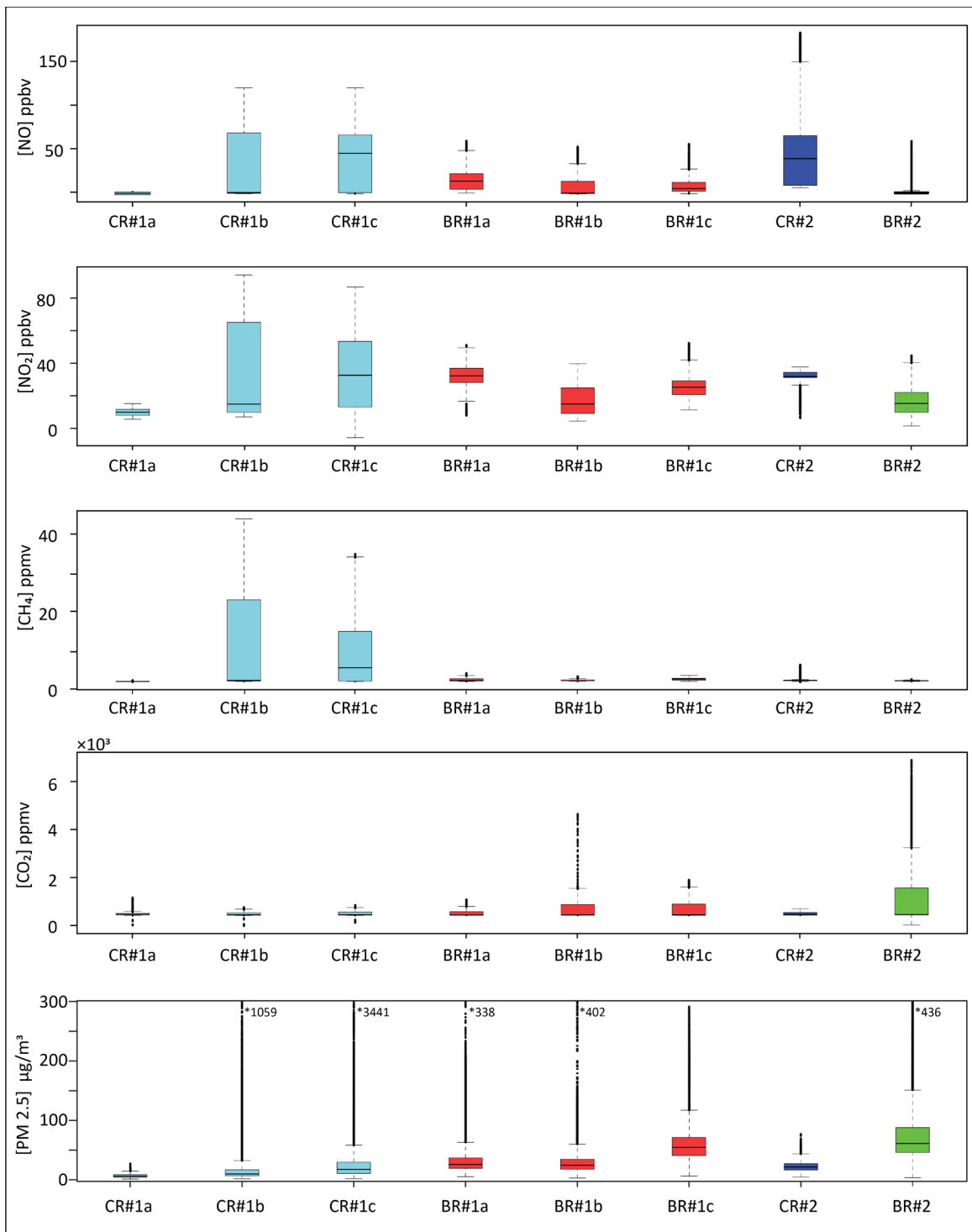


Figure 5: Comparison of NO, NO₂, CH₄, CO₂ and PM_{2.5} concentrations between breweries and coffee roasteries. On each box the central mark indicates the median and the bottom and top edges of the box indicate the 25th and 75th percentiles. Observations above the 95th percentile are plotted using the 'o' symbol. Concentration excursions that extend beyond the y-axis limits for PM_{2.5} are indicated with an * and the maximum concentration is reported.

337 **F_ENO measurements**

338 We measured pre-shift and post-shift F_ENO in the workers from the breweries and coffee roasteries.
 339 These results are summarized in Table 3 and Figure 6. Pre-shift F_ENO levels ranged between 8 – 38 ppb_v, while
 340 post- shift levels ranged between 7 – 51 ppb_v. We used linear mixed models to compare pre-shift F_ENO, post-
 341 shift F_ENO and cross-shift change in F_ENO between breweries and coffee roasteries, controlling for individual
 342 facilities as a random effect. The pre-shift mean F_ENO was 3.7 ppb_v higher [95% confidence interval:-3.6, 11.0]
 343 and the post shift F_ENO was 7.1 ppb_v higher [-1.9, 16.1] for workers at coffee roasteries compared to
 344 breweries. The cross-shift change in F_ENO was 3.4 ppb_v higher [-2.8, 9.6] for workers at coffee roasteries
 345 compared to breweries. Based on the likelihood ratio test, none of these differences were statistically
 346 significant, and the cross shift change in F_ENO was not statistically different from zero for either group of
 347 workers.

348 *Table 3: Summary measures of F_ENO in breweries and coffee roasteries. Concentrations in ppb_v.*

	pre-shift	post-shift	cross-shift change
Breweries (# subjects = 12, # sample pairs = 16)			
median	23	12	7.7
Mean (SD) ^a	22 (11)	22 (12)	0.1 (7.7)
range	8 – 38	7 – 43	-21 – 10
Coffee Roasteries (# subjects = 7, # sample pairs = 10)			
median	24	28	9.0
Mean (SD) ^a	26 (8.0)	29 (12)	3.5 (9.0)
range	17 – 37	12 – 51	-10 – 19

349 ^a(SD) = standard deviation

350

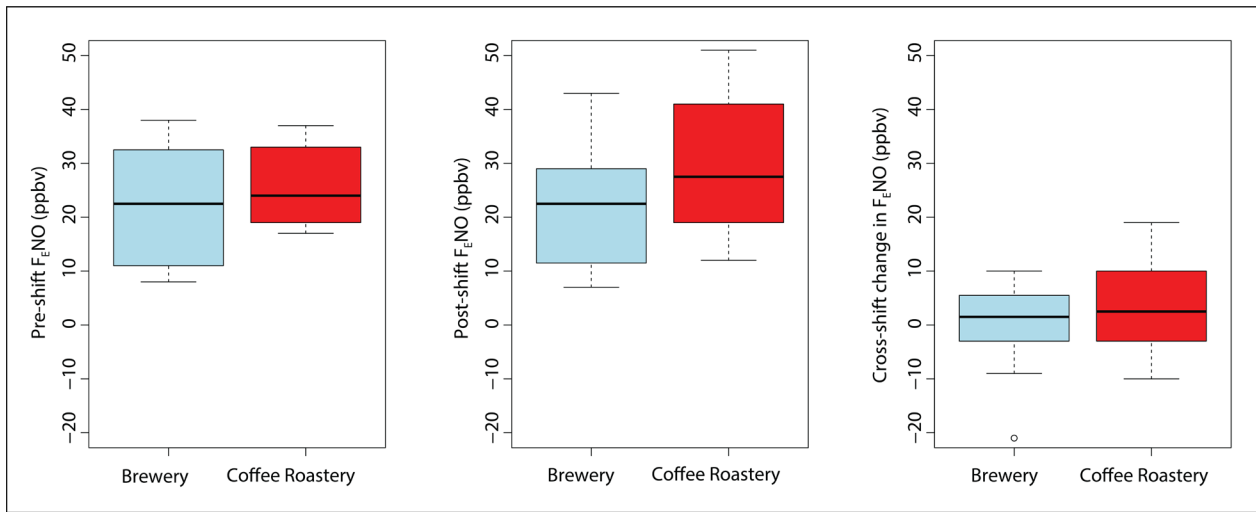


Figure 6: Comparison of pre-shift F_{eNO} , post-shift F_{eNO} and cross-shift change in F_{eNO} between breweries and coffee roasteries. On each box the central mark indicates the median, the bottom and top edges of the box indicate the 25th and 75th percentiles.

356

DISCUSSION

Acetoin, diacetyl and 2,3-pentanedione were measured at concentrations ranging from $< 0.04 - 8$ ppbv using time integrated sorbent sampling techniques. Concentrations varied depending on sampling locations within the facility and type of activities taking place. In general diacetyl and 2,3-pentadione were higher in coffee roasteries compared to breweries. Acetoin was generally higher in breweries. Three samples, all from the barista area at one coffee roastery, exceeded the NIOSH recommended exposure limit (REL) of 5 ppbv for diacetyl. 2,3-Pentanedione concentrations in these three samples were greater than 50% of its REL but did not exceed it.

The time-resolved PTR-ToF-MS measurements followed a similar trend to the sorbent tube data and revealed peak concentrations of diacetyl and 2,3-pentanedione between 15 – 20 ppbv. Examination of the time series data identified specific activities that were associated with peak diketone and acetoin emissions, including transfer of freshly roasted coffee beans to the cooling tray, or opening of a brew kettle at a craft brewery. In general, diacetyl concentrations were the highest of the four diketones measured here, with concentrations decreasing for the higher homologues. The background indoor concentration was less than 2

373 ppb_v for diacetyl and less than 1 ppb_v for all other diketones monitored at both coffee and craft brewing sites
374 during periods with little or no roasting or brewing activities. For example, Figure S16 shows diketone
375 concentrations below 1 ppb_v over the course of a non-roasting workday except for a short transient excursion
376 during the brief transfer of several kilograms of roasted coffee beans. This observation is supported by the low
377 concentrations of diketones reported for integrated sorbent tube samplers. Similar observations were made
378 on Day 2 at BR#1 where ambient background diketone levels of less than 1 ppb_v (Figure 4) were observed.
379 However, during active roasting and brewing days, we observe significant concentration excursions ranging
380 from 5 – 20 ppb_v for diacetyl and 3 – 12 ppb_v for 2,3-pentanedione. The ratio of diacetyl to 2,3-pentandione is
381 roughly 1.6 – 1.7 in the coffee roasting facility. Very little increase in the concentration of the hexane and
382 heptane diones were observed. In one of the breweries, concentrations of diacetyl were observed to increase
383 to 6 – 20 ppb_v associated with opening a kettle lid when boiling wort (Figure 3). Similar concentration
384 timeseries were observed for 2,3-pentanedione, 2,3-hexanedione, and acetoin, although at considerably lower
385 concentrations. The ratio of diacetyl to 2,3-pentandione is roughly 7 – 8 in the brewing facility.

386 The highest diacetyl concentrations were measured at CR#1 and BR#1, with the highest measured
387 concentration below the 15-minute recommended exposure limit of 25 ppb_v. At CR#1, concentrations up to 21
388 ppb_v of diacetyl, 14 ppb_v of 2,3-pentanedione, and 1.2 ppb_v of 2,3-hexanedione were measured. These
389 excursions were short duration (< 5 min) with concentrations approaching background levels after each batch
390 was released from the cooling tray (Figure 2 and Figure S11). Concentration excursions were also measured at
391 the brewery BR#1 on the first and third day of sampling when the brew master opened the mash kettle for
392 process monitoring and to prevent overboiling (Figure 3). The highest acetoin concentrations were recorded at
393 BR#2 (Figure 4), but were not associated with any specific activity, presumably because of the numerous
394 concurrent processes occurring throughout the day.

395 On site survey measurements in which the sampling inlet for the PTR-ToF-MS was moved to different
396 locations revealed elevated diketone concentrations associated with roasted bean storage and grinding

397 activities. For example, the time series data in Figure S12 illustrates diketone concentrations exceeding 2500
398 ppb_v (primarily 2,3-butandione and 2,3-pentandione) in the headspace of bulk storage bins of roasted coffee
399 beans. A similar reconnaissance survey of potential point sources at a craft brewing facility did not reveal
400 notable 'hot spots' for the target analytes.

401 The diacetyl concentrations we measured at the coffee roasteries are similar to those of Echt *et al.*
402 (Echt et al., 2021) who observed some 8-hr TWA exposures above the NIOSH REL of 5 ppb_v for workers
403 involved in coffee bean roasting and grinding at a small-scale craft coffee facility. Pierce *et al.* (Pierce et al.,
404 2015) reported personal diacetyl exposures in the range 13 – 16 ppb_v for a barista grinding and brewing coffee
405 in a residential kitchen – a study designed to simulate potential exposures experienced by baristas and
406 customers in a small commercial coffee shop. In contrast, higher diacetyl and 2,3-pentanedione
407 concentrations (8 – 100 ppb_v) were reported by Baily *et al.* and Duling *et al.*, from a larger commercial coffee
408 processing facility (Bailey et al., 2015, Duling et al., 2016). A summary of diacetyl measurements made in
409 coffee production facilities has recently been published (LeBouf et al., 2020).

410 There are limited data in the literature describing exposures to diacetyl and 2,3-pentanedione in
411 association with brewing of beer. In the only report we found, Eversmeyer reported diacetyl levels < 0.003
412 ppb_v (TWA) and < 0.006 ppb_v (STEL) for two breweries (Eversmeyer, 2016). Our measurements are somewhat
413 higher than those of Eversmeyer but still well below exposure guidelines and suggest that exposures to
414 diacetyl and related compounds in breweries do not exceed health protective levels; however short-term RELs
415 may be exceeded in association with specific processes (e.g., opening the kettle when wort is boiled; see
416 Figure 3).

418 Continuous on-site monitoring

419 Auxiliary air quality parameters (NO, NO₂, CO₂, CH₄ and PM_{2.5}) were measured continuously over eight
420 days of an 8-hr work shift to capture various activities at coffee roasting and craft brewing operations.
421 Background levels were recorded before the start of the workday and found to be similar to ambient outdoor
422 concentrations. Fine particulate matter (PM_{2.5}) was observed to be below 50 µg m⁻³ on non-roasting and
423 brewing days. However, short-term excursions > 300 µg m⁻³ were observed when roasted coffee beans were
424 transferred to the cooling trays at one of the roasting facilities. These excursions are highly episodic and
425 observed to be strongly correlated with diketone concentration excursions (Figure S11). PM_{2.5} was generally <
426 75 µg m⁻³ at brewery facilities but was observed in the range of 100 – 400 µg m⁻³ for periods of several hours
427 associated with the transfer of grains and other materials. Elevated levels of nitrogen oxides (NO and NO₂)
428 were observed during roasting when natural gas furnaces were operational, either for heating coffee roasters
429 or the mash tun in brewing. For example, NO concentrations ranging from 50 – 120 ppb_v and NO₂ levels
430 ranging from 50 – 80 ppb_v were observed during roasting and dropped sharply to levels below 15 ppb_v once
431 the roasting furnaces were turned off (Figure S14). Levels of NO and NO₂ at breweries were generally less than
432 40 ppb_v with some short excursions greater than 40 ppb_v (Figure S15). Measured concentrations of PM_{2.5}, NO₂
433 and NO were all well below OSHA permissible exposure limits. However, the 8-hr TWA PM_{2.5} concentrations
434 measured on roasting days at the coffee facility CR#1 (up to ~30 µg/m³) do exceed the WHO 24-hr PM_{2.5}
435 guideline of 15 µg/m³. Elevated levels of carbon dioxide (CO₂) and methane (CH₄) were observed during coffee
436 roasting reaching levels of 700 ppm_v and 40 ppm_v, respectively. The concentration of both gases dropped to
437 ambient levels once roasting furnaces were shut off (Figure S17). Concentrations of CO₂ at one brewery were
438 between 500 – 1800 ppm_v and between 2 – 6 ppm_v for CH₄. Concentration spikes were largely associated with
439 opening fermentation tanks and bottling activities. Carbon dioxide levels were generally higher at the larger
440 brewery reaching levels of 5000 ppm_v (which is the 8-hr TWA NIOSH REL) late in the afternoon (Figure S18).
441 Given these observations and the emergence of low-cost gas sensors (especially for CO₂ and PM_{2.5}), we

442 recommend that facility operators consider their use to inform ventilation requirements and protect worker
443 safety.

444 Additional field studies are required to strengthen the findings of this study which was limited to a
445 small number of facilities (2 roasteries and 2 breweries) that were also relatively small operations.
446 Measurements were only made during one pilot study period, which does not account for potential seasonal
447 variability. Furthermore, the highest diacetyl concentration recorded was at the barista station at CR#1, where
448 only one sample was collected (n=1). The relationship between PM2.5 and diacetyl in coffee roasting facilities
449 requires further confirmation at additional sites.

450 **Comparison of measured F_ENO levels to ATS guidelines**

451 None of our study participants had elevated F_ENO, defined by ATS as F_ENO > 50 ppb_v (Dweik et al.,
452 2011), and we did not observe any association between F_ENO levels and occupational exposure. In contrast a
453 recent study from Harvey et al. reported that 10% of coffee production workers had elevated F_ENO levels
454 (Harvey et al., 2020). Average diacetyl exposures measured in Harvey's study were much greater than
455 concentrations of diacetyl measured in our study. A cross sectional study of workers in a Tanzanian coffee
456 factory that processed and packed green coffee beans also found that workers had higher F_ENO levels than
457 unexposed controls (Moen et al., 2012). A subsequent study reported coffee production workers had higher
458 prevalence of chronic respiratory and asthma symptoms than workers in two control factories that produced
459 beverages and fish products; F_ENO levels were marginally higher in coffee workers compared to controls
460 (Sakwari et al., 2013).

462 **CONCLUSION**

463 In this pilot study in relatively small-scale coffee roasteries and breweries we found that diacetyl and
464 2,3-pentanedione concentrations were generally below the NIOSH recommended exposure limits. The only

465 exception to this was the 8-hr average concentrations measured near the barista bar where average air
466 concentrations of 7.1 and 7.0 ppb_v for diacetyl and 2,3-pentanedione respectively were observed over the 3-
467 day sampling campaign. Similarly, F_ENO levels were not elevated with respect to ATS guidelines, and no
468 association between occupational exposures and changes in F_ENO was observed.

469 The continuous monitoring capability of the PTR-ToF-MS highlighted the episodic nature of diketone
470 exposures in these facilities and aided in identifying specific tasks associated with these excursions. Elevated
471 concentrations of diketones had strong association with roasting and grinding within coffee facilities. In
472 brewing operations, the potential for exposure to diketones appears to be coincident with opening kettles
473 during boiling of wort. This information can be used to inform when and where better ventilation and/or
474 personal protective equipment might be warranted. Possible short-term exposure to high concentrations of
475 diketones can also occur when employees enter confined coffee storage rooms and when opening storage
476 bins of roasted coffee beans.

477 This report adds to the growing body of literature reporting diketone concentrations that approach or
478 exceed RELs in coffee production facilities. We demonstrate the first use of on-site PTR-ToF-MS at coffee and
479 brewing facilities to directly measure air concentrations of several diketone compounds of concern over a
480 multi-day sampling campaign. The continuous VOC monitoring capabilities of PTR-ToF-MS are especially
481 informative when surveying sites and relating short-term concentration excursions to specific activities. While
482 fine particulate matter may also be an occupational health concern in its own right, its association with
483 diacetyl concentrations in coffee roasting facilities suggest that it may be a suitable proxy for diketone
484 exposure in this setting. The indoor installation of low-cost sensors for CO₂ and PM_{2.5} could be used to monitor
485 ventilation and provide useful operational information.

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