Exposures and Health Effects of Diacetyl and 2,3-Pentanedione in a Coffee Processing Facility

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Abstract

Diacetyl and 2,3-pentanedione are alpha-diketones that are generated during the coffee roasting process and have been shown to be related to respiratory symptoms, abnormal lung function, and in rare cases, an irreversible disease called obliterative bronchiolitis. This study measured personal exposures in a coffee roastery in New Zealand using thermal desorption tubes and explored the prevalence of respiratory symptoms with a health questionnaire.

Exposures from task samples were highest for grinding (Geometric Mean (GM): 22.5 ppb diacetyl; GM: 19.3 ppb 2,3-pentanedione), followed by packaging (GM: 10.8 ppb diacetyl; GM: 9.3 ppb 2,3-pentanedione) and then roasting (GM: 4.7 ppb diacetyl; GM: 4.1 ppb diacetyl). 8-h time-weighted average (TWA) diacetyl exposures exceeded the National Institute of Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) of 5 ppb for Roaster/Packager (GM: 6.6 ppb) and Grinder (GM: 5.3 ppb). 8-h TWA concentrations were below the NIOSH REL of 9.3 ppb for 2,3-pentanedione (Roaster/Packager, GM: 5.7 ppb; Grinder, GM: 4.6 ppb). Workers reported nose, eye symptoms and systemic symptoms (flu-like illness or achy joints, fever or chills, or unusual tiredness or fatigue).

The results indicated that exposure was highest for tasks involving ground coffee beans and that coffee processing workers can be exposed to alpha-diketones above the NIOSH RELs. Further research into alpha-diketone exposure and health effects, and control measures to minimise exposure are recommended.

Keywords

Diacetyl; 2,3-pentanedione; coffee processing; coffee roasting; exposure monitoring; alpha-diketones

1.0 Introduction

Coffee processing is a growing industry in New Zealand with over 14,000 tonnes of unroasted coffee beans worth $77 million imported in 2019 (Stats NZ, 2020). It is currently unknown what exposure levels are in New Zealand coffee processors and what impact exposures have on worker health. Despite its popularity as a beverage worldwide, there has been little attention paid to potential health risks of its process to workers until recently, where researchers investigated the link between exposure to diacetyl and 2,3-pentanedione during the coffee roasting process and subsequent respiratory health effects (Harvey et al. 2020).

Diacetyl was first identified as a constituent of roasted coffee by Johnston and Frey in 1938. In 1974, Kung identified 2,3-pentanedione as a “new caramel compound from coffee”. Both diacetyl and 2,3-pentanedione are volatile organic compounds (VOCs) known as alpha-diketones. Diacetyl is better known as an artificial butter flavouring in microwave popcorn, and in many other food products such as cake mixes, flour, beer, cheese, bakery products and cookies (NTP, 2018). It is also a natural product in dairy products, varieties of fruit and vegetables, beef, poultry, and fish (Triskelion 2017, as cited in Hallagan, 2017). When coffee beans are roasted at 200°C or higher, diacetyl and other alpha-diketones are formed when alanine and glycine amino acids react with glucose and mannose sugars – this is known as the Maillard reaction (Pierce et al., 2015). 2,3-Pentanedione has been used as a substitute for diacetyl because of its related chemical structure and similar flavour properties (NIOSH, 2016).

Flavouring-related obliterative bronchiolitis (OB) was first reported in 1986 in flavouring manufacturing workers in the baking industry by McConnell and Hartle. The causative agent was not identified but a list of the ingredients used at the factory included diacetyl. Some 14 years later, respiratory health effects associated with diacetyl exposures were first reported in eight former workers in a microwave popcorn factory in 2000 (CDC, 2002; Kreiss et al., 2002). They presented with symptoms similar to OB, with cough and dyspnoea upon exertion, and impaired lung function (CDC, 2002). However, it was not until 2013 when the link with coffee processing and OB was first reported by Huff and colleagues. Between 2008 and 2012 at the coffee processing facility in Texas, two workers were exposed to diacetyl, while working in areas with liquid flavourings and subsequently transferred to unflavoured coffee areas, presented with cough, wheeze, shortness of breath on exertion and poor lung function. Lung biopsies confirmed a diagnosis of OB.

Inhalation toxicity studies in rats and mice (Hubbs et al., 2012; Morgan et al., 2012) found that 2,3-pentanedione acted similarly to diacetyl, in that it damages the upper airways epithelium causing fibrotic lesions, which is important as it is an underlying cause of OB (Hubbs et al., 2012; Morgan et al., 2012).

Little was known about 2,3-pentanedione and its toxicity in humans until 2015, when the first cross-sectional exposure surveys on diacetyl and 2,3-pentanedione exposures in coffee processing workers were carried out (Gaffney et al., 2015; Pierce et al., 2015), along with a respiratory health effects study (Bailey et al., 2015). The exposure surveys were considered pilots or hypothesis-generating exercises, and they provided diacetyl and 2,3-pentanedione exposure information from various tasks during coffee processing (Gaffney et al., 2015; Pierce et al., 2015). However, all airborne measurements were area samples as opposed to personal samples which evaluate worker exposure.

From 2017 to 2019, NIOSH carried out a series of Health Hazard Evaluations (HHEs) that collected personal and area measurements of alpha-diketones and respiratory health effects data. Recently, exposure data from the HHE reports were summarised in a study by LeBouf et al. (2020). A total of 415 personal and 606 task samples for diacetyl and 2,3-pentanedione from 17 coffee processing facilities were included for evaluation. "Job groups with the highest personal full-shift exposures to diacetyl and 2,3-pentanedione were packaging workers (Geometric Mean, GM: 8.0 and 4.4 ppb) and production workers (GM: 6.3 and 4.6 ppb) in non-flavoured coffee facilities" (LeBouf et al., 2020).

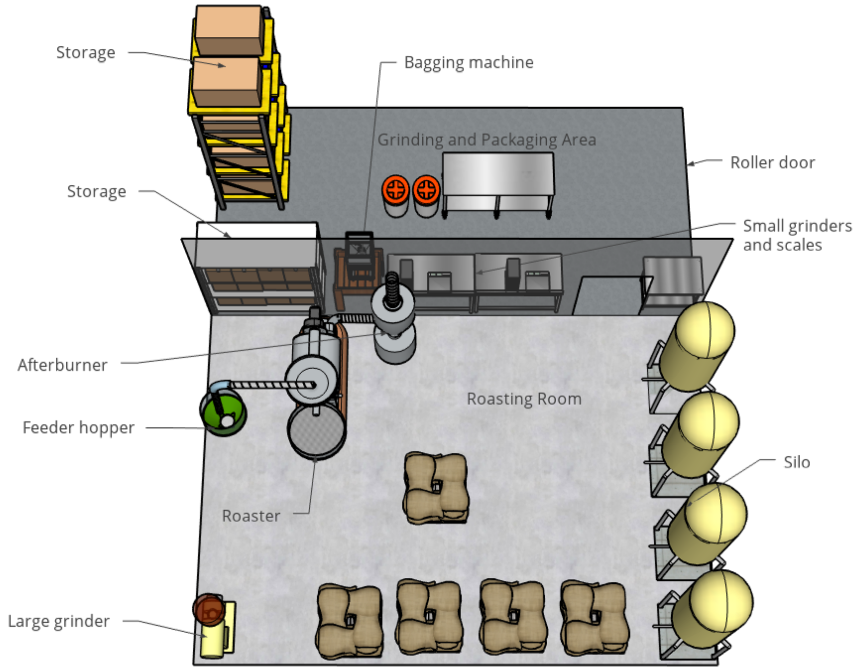
The aims of this project were: to measure personal full-shift exposure to diacetyl and 2,3-pentanedione in coffee processing workers; and to measure the prevalence of respiratory health effects in coffee processing workers using a respiratory health questionnaire. To achieve these aims, we took personal exposure measurements of diacetyl and 2,3-pentanedione and conducted a respiratory symptoms questionnaire in three workers at a coffee processing facility in Christchurch, New Zealand.

2.0 Materials and Methods

2.0.1 Facility Characteristics

The Production Area consisted of a Roasting Room and a Grinding and Packaging Area (see Figure 1). The Roasting Room was a nested structure within the building with an approximate volume of 182 m^3. Natural ventilation was provided through a wall with three small windows and active ventilation was provided by the roasting oven's afterburner with an exhaust stack through the roof.

Figure 1 Floor Plan of Production Area



Access to the Roasting Room was through a sliding door from the Grinding and Packaging Area, which was approximately 287 m^3 in volume . The Grinding and Packaging Area shared an open space with the Storage Area, Retail Area and attached Café, separated only by a partition which did not reach the ceiling. There was a roller door that was sometimes open which provided natural ventilation.

Approximately 2.5 – 3 tonnes of green beans were roasted per week on average. Mondays, Wednesdays and Fridays were usually for grinding, packaging and bagging. Friday mornings were for grinding larger quantities (approximately 100 – 200 kg). Tuesdays and Thursdays were roasting days in the morning, with packaging in the afternoon.

2.0.2 Process and Task Description

The main steps in coffee processing at this facility are: (1) receiving green beans, (2) roasting green beans, (3) grinding roasted beans, (4) bagging roasted or ground coffee, (5) packaging coffee for distribution.

Green coffee beans were received in hessian sacks and stored in the storage area or roasting room for immediate use. The roasting process begins with the first batch, where a worker (Roaster/Packager) scoops grean beans from hessian sacks into a plastic bucket then filling the roaster oven's hopper with 60 kg of beans. The beans were sucked up by an extractor into the roasting oven and roasted above 200°C for approximately 20 minutes. The roaster drum is opened and the roasted beans spill out onto the cooling tray where downdraft extraction cools the beans down and also removes any smoke and vapour. The beans were transferred to a silo using a blower connected to a duct. After roasting, the Roaster/Packager operator would grind small quantities of beans (200 g to 1 kg) throughout the rest of the work shift, weigh bags, label, and pack them in cardboard boxes or immediately sell them as ordered.

Once a week, a Grinder worker would use a large grinder in the Roasting Room to grind approximately 100 kg of roasted coffee beans. A large plastic container is filled with roasted beans from the silo, where 12-16 kg of roasted coffee beans at a time were transferred into the large grinder. Once ground up, another 12-16 kg of roasted coffee beans were transferred into the large grinder while the ground coffee is taken to the bagging machine. The ground coffee was filled into 1 kg bags, heat sealed, then packed into cardboard boxes. The boxes were placed onto the storage shelf ready for dispatch. The worker went back to the large grinder to start the next cycle of bagging ground coffee and this cycle was repeated until finished.

2.0.3 Workforce Description

The workers were divided into four similar exposure groups (SEG): Roaster/Packager, Grinder, Barista, and Office.

The Roaster/Packager (n=2) alternated days of roasting coffee beans. While one worker was roasting, the other one was packaging. Once roasting was finished, they would both assist with grinding, bagging, and packaging. The Roaster/Packagers' tasks consists of roasting on Tuesdays and Thursdays from approximately 08:30 – 14:00, followed by a combination grinding small amounts of roasted coffee, bagging and packaging for the rest of the shift. On the remaining days of the week they carry out a combination of the aforementioned activities minus roasting, barista work in the café, and administrative tasks.

The Grinder's (n=1) tasks consisted of: grinding approximately 100 kg of roasted coffee on Fridays from approximately 08:30 – 11:00, and bagging and packaging for the rest of the shift. On the remaining days of the week they carred out a combination of barista work in the café, packaging, or work off-site.

The Barista (n=1) worked in the café preparing coffee and food. The Office workers (n=2) performed administrative tasks in the office adjacent to the Grinding and Packaging Area.

2.0.4 Sampling Strategy

A walkthrough survey was carried out to observe the processes and tasks, potential sources of exposure, existing controls, identify SEGs, and recruit participants for this study. This research was reviewed and approved by the Health and Medical Human Research Ethics Committee of the University of Wollongong (Reference: 2020/258).

The SEGs recruited for the study were those of highest risk of exposure to alpha-diketones (e.g. roasters, grinding, and packaging workers) as identified in the literature (Duling et al., 2016; McCoy et al., 2017; Pengelly et al., 2019). Thus, two Roaster/Packagers and one Grinder were recruited.

Personal sampling of each worker was carried out for the duration of the task or between 80 and 180 minutes. Two task samples per day were taken for the Roaster/Packager and one sample per day was taken for the Grinder. The sampling was undertaken on Thursdays and Fridays over two weeks, i.e. on days 1, 7, and 14 for the Roaster/Packager and on days 2, 8 and 15 for the Grinder.

2.0.5 Air Sampling and Analysis

Nine personal task samples were collected for diacetyl and 2,3-pentanedione over a two week period in October 2020. Sampling was undertaken according to a modified method from Pengelly (2018) using stainless steel thermal desorption (TD) tubes, packed with 300 mg of Tenax TA (60/80 mesh) that was retained between two steel gauzes. Aluminium end caps fitted with polytetrafluoroethylene (PTFE) ferrules were affixed on each end of the TD tubes.

The TD tubes were connected in series to the sampling pump (SKC AirChek XR5000) pulling air through the tube at a rate of 25 to 75 ml/min. The tubes were clipped onto the breathing zone of the worker for the duration of the task or for up to 180 minutes. One blank sample per day of sampling was taken for quality assurance. After sampling, the TD tubes were sealed and sent to the same NATA-accredited laboratory (ChemCentre, Western Australia) that provided the TD tubes for analysis by gas chromatography – mass spectrometry (GC-MS). The limit of reporting for this method was 50 ng/tube.

To calculate the full-shift TWA, it was assumed that the task-based sample concentrations were representative over the usual duration of the tasks, based on discussions with the operators and observations. For the Roaster/Packager, it was assumed that Roasting was conducted for 240 minutes, Packaging for 180 minutes, and zero exposure for the lunch break and other tasks for the remaining 60 minutes of the shift. For the Grinder, it was assumed that grinding was conducted for the duration of the measurement period (80-150 minutes) and zero exposure for the remainder of the shift.

The 8-h TWA concentrations were compared with the NIOSH REL of 5 ppb for diacetyl and 9.3 ppb for 2,3-pentanedione. The task samples, although greater than 15 minutes in duration, were compared with NIOSH STEL of 25 ppb for diacetyl and 31 ppb for 2,3-pentanedione.

2.0.6 Respiratory Symptoms Questionnaire

Participants were administered a respiratory symptoms questionnaire derived from the International Union Against Tuberculosis Bronchial Symptoms Questionnaire (IUATLD/UICTMR 1984, as cited in Safe Work Australia, 2013) and NIOSH HHE reports. The questionnaire was supplemented to include a question on electronic cigarette use as diacetyl and 2,3-pentanedione may be present in flavoured liquids of electronic cigarettes (Allen et al., 2016). The prevalence of health symptoms per SEG were reported.

The three workers who participated in this assessment and questionnaire were over 18 years of age. There were two male (67%) and one female (33%) participants with a mean age of 34 years. The average tenure at the company was 6 years and the average duration in the coffee processing industry was 10 years. One worker (33%) was never a smoker, one worker (33%) was a former smoker and one worker (30%) is a current smoker. Two workers (67%) reported performing roasting, small amounts of grinding and packaging; while one worker (33%) reported performing large amounts of grinding, packaging, and other tasks as their main role.

2.0.7 Ventilation Assessment

Air current tubes were utilised to determine if the Roasting Room was under negative pressure. Smoke was blown around the edges of the sliding door between the Roasting Room and Grinding and Packaging Area. Visual observations of smoke being drawn into the Roasting Room from the Grinding and Packaging Area indicated negative pressure in the Roasting Room. Smoke was also blown around the edges of the windows and it was observed that air was entering the Roasting Room rather than blowing out.

Face velocities of the roasting oven's cooling tray were measured using an air velocity meter (TSI® VelociCalc® 9565) using a 6-point traverse over the face of the cooling tray, adapted from a circular duct traverse (ACGIH®, 1998). The cooling tray was 1.6 m in diameter and had an area of 2.0 m^2.

The average face velocity was compared with the recommended range of capture velocities for contaminants released at low velocity into moderately still air, which is 0.5-1.0 m/s (ACGIH®, 1998).

2.0.8 Data Analysis

For diacetyl and 2,3-pentanedione exposures, measurements below the limit of reporting were substituted with the limit of reporting divided by two, for data analysis. One-way Analysis of Variance (ANOVA) tests were used to test the null hypothesis that the means of several populations were all equal. A p-value of <0.05 indicated that at least one mean of the three tasks was different. Subsequent independent two-tail t-tests were performed between each task or SEG to compare the means of each task or SEG for significance (p<0.05). Statistical analyses were performed in Microsoft Excel®.

3.0 Results

3.0.1 Diacetyl and 2,3-Pentanedione – Task Samples

Grinding resulted in the highest diacetyl concentration of 27 ppb, which exceeded the NIOSH STEL. No other diacetyl or 2,3-pentanedione exposures exceeded the NIOSH STEL (Table 1). Grinding had the highest diacetyl and 2,3-pentanedione geometric mean concentrations. Roasting had the lowest geometric mean concentrations. Diacetyl concentrations were higher than 2,3-pentanedione for all tasks, but this was not statistically significant (P>0.05).

Table 1 Diacetyl and 2,3-Pentanedione Exposure Concentrations

Task	Day	Sampling Time (mins)	Diacetyl Concentration (ppb)	2,3-Pentanedione Concentration (ppb)
Roasting	1	180	6.1	5.2
	7	80	7.9	6.8
	14	120	<4.4*	<3.8*
	GM		**4.7**	**4.1**
	GSD		**2.0**	**2.0**
Packaging	1	151	7.2	6.2
	7	122	19	17
	14	90	9.0	7.8
	GM		**11**	**9.3**
	GSD		**1.7**	**1.7**
Grinding	2	80	27**	23
	8	150	19	16
	15	120	23	19
	GM		**23**	**19**
	GSD		**1.2**	**1.2**
NIOSH STEL			**25**	**31**

*<Limit of Reporting, substituted with limit of reporting divided by two for calculating the average
******, concentration above NIOSH STEL; GM, Geometric Mean; SD, Standard Deviation.

The ANOVA single factor test identified a significant difference of the mean diacetyl and 2,3-pentanedione concentrations between the tasks (p=0.01). Thus, subsequent analysis using an independent t-test showed only a significant difference of the means between Roasting and Grinding (p<0.01) for both diacetyl and 2,3-pentanedione (see Figures 2 and 3).

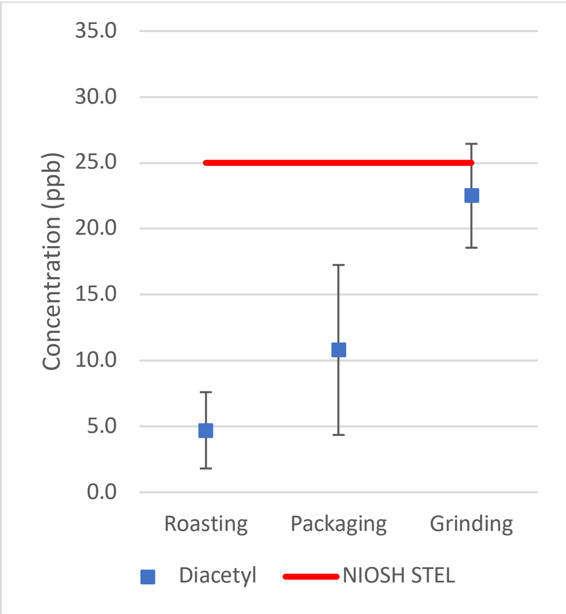


Figure 2 Geometric means of diacetyl exposures with one standard deviation (as error bars) compared with the NIOSH STEL

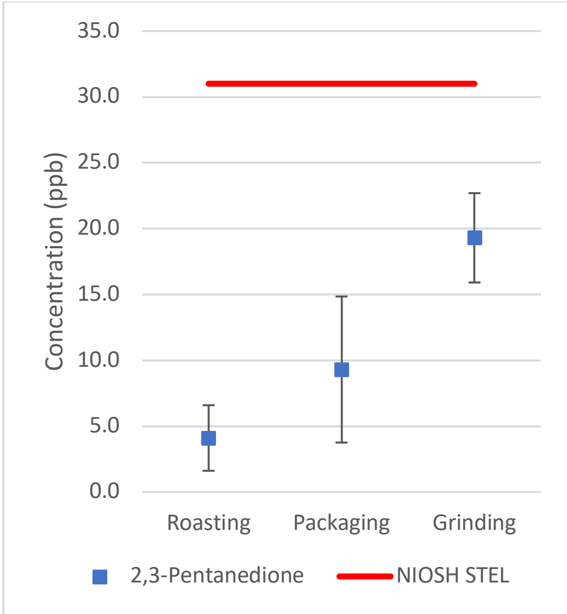


Figure 3 Geometric means of 2,3-pentanedione exposures with one standard deviation (as error bars) compared with the NIOSH STEL

3.0.2 Diacetyl and 2,3-Pentanedione – 8-h TWA Samples

Roaster/Packager had the highest diacetyl and 2,3-pentanedione concentrations of 11.1 ppb and 9.6 ppb, respectively. Two out of three (67%) diacetyl concentrations exceeded the NIOSH REL. One out of three (33%) 2,3-pentanedione concentrations exceeded the NIOSH REL (Table 2).

For Grinder, two out of three (67%) diacetyl concentrations exceeded the NIOSH REL. None of the 2,3-pentanedione concentrations exceeded the NIOSH REL (Table 2).

Table 2 8-h TWA diacetyl and 2,3-pentanedione concentrations

SEG	Day	Diacetyl Concentration (ppb)	2,3-Pentanedione Concentration (ppb)
Roaster/Packager	1	5.7**	4.9
	3	11**	9.6**
	5	4.5	3.9
	GM	**6.6****	**5.7**
	GSD	**1.6**	**1.6**
Grinder	2	4.5	3.8
	4	5.9**	5.1
	6	5.7**	4.9
	GM	**5.3****	**4.6**
	GSD	**1.2**	**1.2**
NIOSH REL		**5**	**9.3**

**, concentration above NIOSH REL; GM, Geometric Mean; GSD, Geometric Standard Deviation.

The Roaster/Packager had higher diacetyl and 2,3-pentanedione geometric mean concentrations than the Grinder (Figures 4 and 5). However, there were no significant differences between the geometric means of Roaster/Packager and Grinder for diacetyl or for 2,3-pentanedione (P>0.05). Diacetyl concentrations were higher than 2,3-pentanedione for both SEGs, but this was not statistically significant (P>0.05).

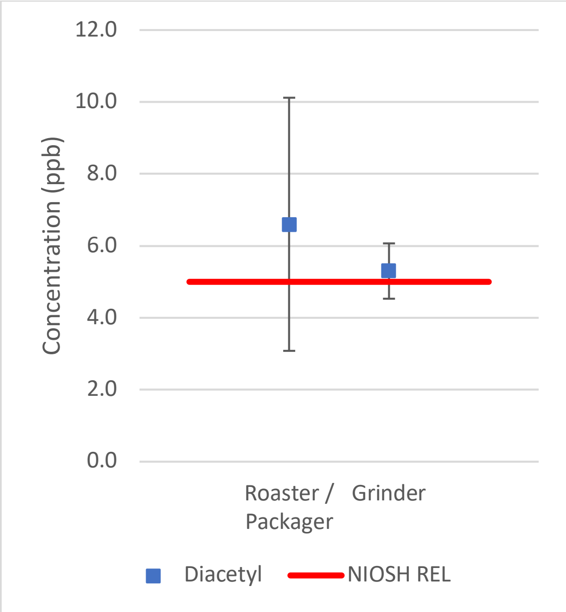


Figure 4 Geometric means of diacetyl exposures with one standard deviation (as error bars) compared with the NIOSH REL

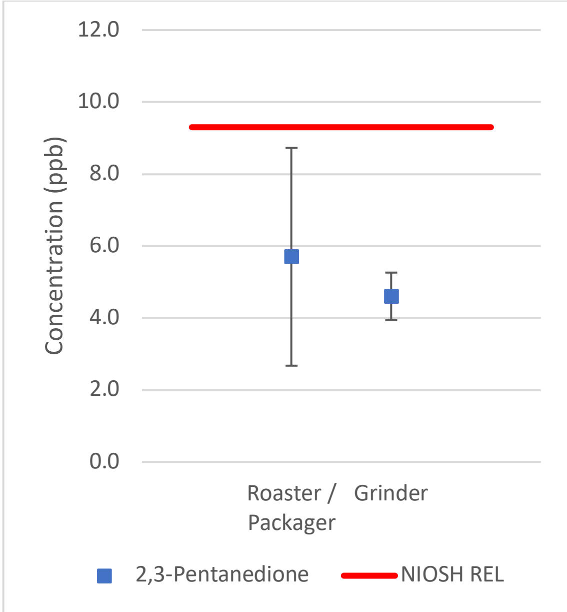


Figure 5 Geometric means of 2,3-Pentanedione exposures with one standard deviation (as error bars) compared with the NIOSH REL

3.0.3 Respiratory Symptoms

One worker reported experiencing nose and eye symptoms in the last 12 months (33%) and within the previous 4 weeks (33%). None of the 3 workers reported any lower respiratory symptoms. Two workers reported one or more systemic symptoms in the last 12 months (67%): episodes of flu-like achiness or achy joints (67%), episodes of fever or chills (50%), and unusual tiredness or fatigue (67%). Only one worker's symptoms occurred within the previous 4 weeks (episodes of fever or chills) (see Table 3).

Table 3 Prevalence of Reported Symptoms

Symptom	Experienced in the last 12 months N=3 Number (%)	Experienced in the last 4 weeks N=3 Number (%)
Nose symptoms*	1 (33%)	1 (33%)
Eye symptoms†	1 (33%)	1 (33%)
Sinusitis or sinus problems	0 (0%)	0 (0%)
Problem with ability to smell	0 (0%)	—
Phlegm on most days for 3 months	0 (0%)	—
Lower respiratory symptoms (reported at least one of the following)‡ **Asthma attack$^{\alpha}$ / Awoke with chest tightness / Awoke with shortness of breath / Breathing trouble / Chest wheezing or whistling / SOB on level ground or walking up a slight hill / Usual cough$^{\beta}$**	0 (0%)	0 (0%)
Systemic symptoms (reported at least one of the following)	2 (67%)	2 (67%)
Episodes of flu-like achiness or achy joints	2 (67%)	2 (67%)
Episodes of fever or chills	2 (67%)	1 (33%)
Unusual tiredness or fatigue	2 (67%)	2 (67%)

*N, number of participants; SOB, shortness of breath; "—", A four-week question was not asked for the symptom; * Nose symptoms includes one or both of the following: 1) stuffy, itchy, or runny nose or 2) stinging, burning nose; † Eye symptoms includes one or both of the following: 1) watery, itchy eyes or 2) stinging, burning eyes; ‡ All four of the participants with one or more lower respiratory symptoms reported these respiratory symptoms did not improve when away from the workplace; α A four-week question was not asked* *for the symptom; β This question did not specifically ask about a cough within the past 12 months; participants were asked, "Do you usually have a cough?" If the participant answered yes to that question, they were then asked, "Have you had a cough at any time in the last 4 weeks?"*

3.0.4 Ventilation Assessment

The average face velocity of the roasting oven's cooling tray was 0.75 m/s, which was within the recommended range for contaminants released at low velocity into moderately still air, which is 0.5-1.0 m/s (ACGIH®, 1998). It was observed that the downdraft extraction of the cooling tray was further enhanced by the machine guarding which semi-enclosed the cooling tray, and visible emmissions were drawn into the cooling tray when the roasting oven door was opened.

4.0 Discussion

4.0.1 Diacetyl and 2,3-Pentanedione – 8-h TWA Samples

Roaster/Packager 8-h TWA geometric means of 7.1 ppb for diacetyl and 6.1 ppb for 2,3-pentanedione were similar to those reported for similar SEGs in the NIOSH HHEs and a previous study (McCoy et al., 2017) but lower than Roasters in Duling et al (2016). In Pengelly and colleagues' (2019) study, workers in Roasting had generally lower levels of <5 ppb. Geometric means for Roaster operators (n=34) were 5.1 ppb for diacetyl and 3.3 ppb for 2,3-pentanedione. Geometric means for Packaging workers (n=41) were 8.0 ppb for diacetyl and 4.4 ppb for 2,3-pentanedione (LeBouf et al., 2020).

Grinder 8-h TWA geometric means of 5.3 ppb for diacetyl and 4.6 ppb for 2,3-pentanedione were lower than those in several studies (Duling et al., 2016; Pengelly et al., 2019; LeBouf et al., 2020), and similar to a previous study (McCoy et al., 2017). Grinder operators (n=3) maximum TWA were 11 ppb for diacetyl and 6.2 ppb for 2,3-pentanedione (LeBouf et al., 2020). The maximum concentration was reported because less than five measurements were above the detection limit. Therefore, the average concentration for Grinder operators in LeBouf et al. (2020) could be lower.

Roaster/Packager TWA exposures had higher diacetyl and 2,3-pentanedione GM concentrations than the Grinder SEG. When compared with the task samples, Grinding had higher concentrations than Roasting and Packaging. This may be explained by Grinding consisting of grinding large quantities (approximately 100 kg) of roasted coffee compared with grinding smaller amounts during Packaging. However, this task is only performed on Fridays for 80-150 minutes. When zero exposure is assumed for the rest of the work shift, the TWA decreases.

4.0.2 Diacetyl and 2,3-Pentanedione – Task Samples

Roasting task concentrations of GM 4.7 ppb for diacetyl and GM 4.1 ppb for 2,3-pentanedione were higher than in the NIOSH HHEs. GMs for roasting coffee beans (n=152) were 2.6 ppb for diacetyl and 2.4 ppb for 2,3-pentanedione (LeBouf et al., 2020).

Packaging task concentrations of GM 10.8 ppb for diacetyl and GM 9.3 ppb for 2,3-pentanedione were higher than in the NIOSH HHEs. GMs for packaging coffee (n=153) were 8.6 ppb for diacetyl and 5.3 ppb for 2,3-pentanedione (LeBouf et al., 2020).

Grinding task concentrations of GM 22.5 ppb for diacetyl and GM 19.3 ppb for 2,3-pentanedione were lower than in the NIOSH HHEs. GMs for grinding coffee beans (n=58) were 26 ppb for diacetyl and 20 ppb for 2,3-pentanedione (LeBouf et al., 2020). However, the grinding task diacetyl results were still lower than short-term measurements for two Grinder workers of 30 ppb and 80 ppb (McCoy et al., 2017).

Although there were slight differences between the GMs of the tasks between this study and the NIOSH HHEs (LeBouf et al. 2020), the exposure concentrations shared a similar pattern – higher exposure levels in grinding, followed by packaging, and the lowest exposure levels in roasting. It has hypothesized that ground coffee has a greater surface area than whole beans, which may increase emission levels for grinding (Gaffney et al., 2015; Pengelly et al., 2019). Workers in close proximity to sources of emissions had higher exposure levels in previous studies, which could explain why Packaging had the next highest exposures in this study, as these workers were near stored roasted coffee beans and ground coffee in the bagging area (McCoy et al., 2017; Pengelly et al., 2019).

4.0.3 Respiratory Symptoms

One worker reported eye and nose symptoms within the last 4 weeks and over the last 12 months. Nose and eye symptoms have been reported as the most common symptoms in several other studies in coffee processing workers (Hawley et al., 2017; LeBouf, Martin Jr, Mugford, et al., 2017; LeBouf, Martin Jr, Stanton, et al., 2017; Duling et al., 2018; Fechter-Leggett, Duling, et al., 2018; Fechter-Leggett, Johnson, et al., 2018; Harvey et al., 2018; Martin Jr et al., 2018; McClelland et al., 2019). A study summarising the NIOSH HHEs results showed that 49% (n=187) of workers reported eye symptoms in the last 12 months and 30% (n=117) in the last 4 weeks (Harvey et al., 2020). Also, 64% (n=244) of workers reported nose symptoms in the last 12 months and 38% (n=145) in the last 4 weeks. It was possible that the symptoms experienced in this study were due to other contributors rather than alpha-diketones. Workers in previous studies reported that the symptoms were caused or aggravated by dust, green coffee dust, hessian sack dust, or chaff (Hawley et al., 2017; LeBouf, Martin Jr, Mugford, et al., 2017; LeBouf, Martin Jr, Stanton, et al., 2017; Duling et al., 2018; Fechter-Leggett, Duling, et al., 2018; Fechter-Leggett, Johnson, et al., 2018; Harvey et al., 2018; Martin Jr et al., 2018; McClelland et al., 2019). Duling et al. (2016) note that Roaster workers' exposure to "particles from dumping of coffee beans and smoke generated from roasting" may be responsible for work-related symptoms.

Systemic symptoms were reported in 67% of workers in our study. Episodes of flu-like achiness or achy joints and episodes of fever or chills are not specific to dust or alpha-diketone exposure. These symptoms were reported by the workers to be cold or flu-like symptoms, and it was unlikely they were related to exposures at work. In the NIOSH HHEs, systemic symptoms were experienced in the last 12 months by 52% (n=199) of workers and 24% (n=94) in the last 4 weeks (Harvey et al., 2020).

4.0.4 Ventilation

The face velocity measurements were taken when there were coffee beans in the cooling tray. Otherwise, it would be expected that the average face velocity would be higher if there were no coffee beans. The average face velocity of 0.75 m/s was adequate and performs to the recommended level of 0.5-1.0 m/s for contaminants released at low velocity into moderately still air (ACGIH®, 1998).

It would be expected that alpha-diketone exposures in the Roasting Room would be lower than in the Grinding and Packaging area, given the performance of the downdraft extraction in the cooling tray and lack of engineering controls in the Grinding and Packagin area. However, other sources of exposure during the Roasting task include potential off-gassing from roasted coffee beans stored in the silos of the Roasting Room; packaging, bagging and small grinding as the work can be heterogenous when roasting; and possible transfer of alpha-diketones from the Grinding and Packaging Area to the Roasting Room as it was under slight negative pressure. Low and non-detectable concentrations of alpha-diketones have been seen in coffee processing facilities even with robust ventilation systems (McCoy et al., 2017).

4.0.5 Limitations

The study was conducted over a two-week period on Thursdays and Fridays, chosen to be representative of normal production. However, not considered were seasonal and peak periods of production that could change the volume of processing. Sampling at different times of the year may give a more representative characterisation of worker exposure. Furthermore, this study focused only on one facility, which limits the ability to generalise results to the wider industry.

It was not possible to carry out detailed statistical analysis on the alpha-diketone measurements as the number samples in this study was small. Moreover, Roaster/Packager and Grinder have heterogeneity in their tasks. Therefore, the results may not reflect their true exposure over time and should be interpreted with caution as variance (within worker, between workers, and between days) is likely to be high.

The sampling method used had a maximum sampling duration of 180 minutes. Therefore, two task samples per day were taken for the Roaster/Packager, with assumptions made in the representativeness of exposure for the remaining duration of the tasks and zero exposures for non-production tasks to calculate their full shift TWA. For the Grinder, one task sample per day was taken and assumptions were made for the remaining duration of the task and zero exposure for non-production tasks. When assumptions are made, this increased uncertainty of the representativeness of exposure in the calculated full shift TWAs.

The task samples were greater than 15 minutes in duration. When compared with the NIOSH STEL of 25 ppb for diacetyl and 31 ppb for 2,3-pentanedione, peak concentrations during a 15 minute period may be averaged over a longer period of time, thereby underestimating exposure.

Respiratory symptoms data were not obtained from the roasteries' non-production workers, workers from a non-exposed occupation, or from the general population to serve as comparison groups or controls. It cannot be ruled out that the prevalence of symptoms observed were normal and expected, as opposed to being caused by alpha-diketone or dust exposure.

5.0 Conclusion

The NIOSH REL for diacetyl was exceeded by the Roaster/Packager and Grinder SEGs but the NIOSH REL for 2,3-pentanedione was not exceeded. Task sample concentrations were highest for Grinding, followed by Packaging, and lowest for Roasting. Workers in both SEGs reported nose and eye symptoms, but it cannot be ruled out that this may be linked exposures other than alpha-diketones.

This study is believed to be the first to measure personal exposure to alpha-diketones in New Zealand coffee processing workers. Exposure to diacetyl and 2,3-pentanedione is a potential occupational health hazard that the New Zealand coffee processing industry should be made aware of. Further research into alpha-diketone exposure and health effects, and control measures to minimise risks to health are recommended.

Declaration

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6.0 References

ACGIH®. (1998) Industrial Ventilation - A Manual of Recommended Practice. Cincinnati, Ohio: American Conference of Governmental Industrial Hygienists.

Allen JG, Flanigan SS, LeBlanc M, Vallarino J, MacNaughton P, Stewart JH, Christiani DC. (2016) Response to "Comment on 'Flavoring chemicals in e-cigarettes: diacetyl, 2, 3-pentanedione, and acetoin in a sample of 51 products, including fruit-, candy-, and cocktail-flavored e-cigarettes'". Environmental Health Perspectives; 124: A102-A03.

Bailey RL, Cox-Ganser JM, Duling MG, LeBouf RF, Martin SB, Jr., Bledsoe TA, Green BJ, Kreiss K. (2015) Respiratory morbidity in a coffee processing workplace with sentinel obliterative bronchiolitis cases. Am J Ind Med; 58: 1235-45.

CDC. (2002) Fixed obstructive lung disease in workers at a microwave popcorn factory--Missouri, 2000-2002. MMWR. Morbidity and mortality weekly report; 51: 345.

Duling MG, Harvey RR, Stanton ML, Lawrence RB, McClelland TL, Nett RJ. (2018) Health hazard evaluation report: Evaluation of exposures and respiratory health at two coffee roasting and packaging facilities. Book Health hazard evaluation report: Evaluation of exposures and respiratory health at two coffee roasting and packaging facilities, City: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Duling MG, LeBouf RF, Cox-Ganser JM, Kreiss K, Martin SB, Bailey RL. (2016) Environmental characterization of a coffee processing workplace with obliterative bronchiolitis in former workers. Journal of occupational and environmental hygiene; 13: 770-81.

Fechter-Leggett ED, Duling MG, Johnson AR, Boylstein RJ, Beaty MC. (2018) Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility. Book Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility, City: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Fechter-Leggett ED, Johnson AR, Martin Jr SB, Grant MP. (2018) Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and flavoring facility. Book Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and flavoring facility, City: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Gaffney SH, Abelmann A, Pierce JS, Glynn ME, Henshaw JL, McCarthy LA, Lotter JT, Liong M, Finley BL. (2015) Naturally occurring diacetyl and 2,3-pentanedione concentrations associated with roasting and grinding unflavored coffee beans in a commercial setting. Toxicology Reports; 2: 1171-81.

Hallagan JB. (2017) The use of diacetyl (2,3-butanedione) and related flavoring substances as flavorings added to foods-Workplace safety issues. Toxicology; 388: 1-6.

Harvey RR, Fechter-Leggett ED, Bailey RL, Edwards NT, Fedan KB, Virji MA, Nett RJ, Cox-Ganser JM, Cummings KJ. (2020) The burden of respiratory abnormalities among workers at coffee roasting and packaging facilities. Frontiers in public health; 8: 5.

Harvey RR, Hawley B, Martin Jr SB. (2018) Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility. Book Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility, City: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Hawley B, Martin Jr SB, Duling MG, Bailey RL. (2017) Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility. Book Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility, City: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Hubbs AF, Cumpston AM, Goldsmith WT, Battelli LA, Kashon ML, Jackson MC, Frazer DG, Fedan JS, Goravanahally MP, Castranova V. (2012) Respiratory and olfactory cytotoxicity of inhaled 2, 3-pentanedione in Sprague-Dawley rats. The American journal of pathology; 181: 829-44.

Huff S, Stocks JM, Saito R, Bilhartz P, Levin J, Glazer C, Bailey R, Cummings K, Kreiss K, McCague A. (2013) Obliterative bronchiolitis in workers in a coffee-processing facility—Texas, 2008–2012. MMWR. Morbidity and mortality weekly report; 62: 305.

Johnston WR, Frey CN. (1938) The Volatile Constituents of Roasted Coffee. Journal of the American Chemical Society; 60: 1624-27.

Kreiss K, Gomaa A, Kullman G, Fedan K, Simoes EJ, Enright PL. (2002) Clinical bronchiolitis obliterans in workers at a microwave-popcorn plant. New England Journal of Medicine; 347: 330-38.

Kung JFT. (1974) New Caramel Compound from Coffee. Journal of Agricultural and Food Chemistry; 22: 494-96.

LeBouf RF, Blackley BH, Fortner AR, Stanton M, Martin SB, Groth CP, McClelland TL, Duling MG, Burns DA, Ranpara A. (2020) Exposures and Emissions in Coffee Roasting Facilities and Cafés: Diacetyl, 2, 3-Pentanedione, and Other Volatile Organic Compounds. Frontiers in public health; 8: 527.

LeBouf RF, Martin Jr SB, Mugford C, Stanton ML, Bailey RL. (2017) Health hazard evaluation report: Evaluation of exposure and respiratory health at a coffee processing facility. Book Health hazard evaluation report: Evaluation of exposure and respiratory health at a coffee processing facility, City: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

LeBouf RF, Martin Jr SB, Stanton ML, Mugford C, Bailey RL. (2017) Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility and attached retail café. Book Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility and attached retail café, City: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Martin Jr SB, LeBouf RF, Stanton ML, Bailey RL. (2018) Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility and associated café. Book Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility and associated café, City: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

McClelland TL, Boylstein RJ, Martin SB, Beaty M. (2019) Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility and two off-site retail cafés. Book Health hazard evaluation report: Evaluation of exposures and respiratory health at a coffee roasting and packaging facility and two off-site retail cafés, City: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

McConnell R, Hartle R. (1986) Hazard evaluation and technical assistance report: International Bakers Services, Inc, South Bend, IN. Book Hazard evaluation and technical assistance report: International Bakers Services, Inc, South Bend, IN, City: U.S. Department of Health and Human Services, Centers for Disease Control, National Institute for Occupational Safety and Health.

McCoy MJ, Hoppe Parr KA, Anderson KE, Cornish J, Haapala M, Greivell J. (2017) Diacetyl and 2,3-pentanedione in breathing zone and area air during large-scale commercial coffee roasting, blending and grinding processes. Toxicology Reports; 4: 113-22.

Morgan DL, Jokinen MP, Price HC, Gwinn WM, Palmer SM, Flake GP. (2012) Bronchial and bronchiolar fibrosis in rats exposed to 2,3-pentanedione vapors: implications for bronchiolitis obliterans in humans. Toxicol Pathol; 40: 448-65.

NIOSH. (2016) Criteria for a Recommended Standard. Occupational Exposure to Diacetyl and 2,3-Pentanedione. In McKernan LT NR, Kreiss K, Hubbs A, Park R, Dankovic D, Dunn KH, Parker J, Fedan K, Streicher R, Fedan J, Garcia A, Whittaker C, Gilbert S, Nourian F, Galloway E, Smith R, Lentz TJ, Hirst D, Topmiller J, Curwin B editor. Book Criteria for a Recommended Standard. Occupational Exposure to Diacetyl and 2,3-Pentanedione, City: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

NTP. (2018) NTP Technical Report on the Toxicology and Carcinogenesis Studies of 2,3-butanedione (CAS No. 431-03-8) in Wistar HAN [Crl: WI (Han)] Rats and B6C3F1/N Mice (Inhalation Studies). Book NTP Technical Report on the Toxicology and Carcinogenesis Studies of 2,3-butanedione (CAS No. 431-03-8) in Wistar HAN [Crl: WI (Han)] Rats and B6C3F1/N Mice (Inhalation Studies), City: National Toxicology Program (NTP), National Institutes of Health, Public Health Service, U.S. Department of Health and Human Services.

Pengelly I. (2018) Validation of a measurement method for diacetyl using sorbent tubes and thermal desorption. Book Validation of a measurement method for diacetyl using sorbent tubes and thermal desorption, City.

Pengelly I, O'Shea H, Smith G, Coggins MA. (2019) Measurement of Diacetyl and 2,3-Pentanedione in the Coffee Industry Using Thermal Desorption Tubes and Gas Chromatography-Mass Spectrometry. Annals of work exposures and health; 63: 415-25.

Pierce JS, Abelmann A, Lotter JT, Comerford C, Keeton K, Finley BL. (2015) Characterization of naturally occurring airborne diacetyl concentrations associated with the preparation and consumption of unflavored coffee. Toxicology Reports; 2: 1200-08.

Safe Work Australia. (2013) Health Monitoring for Exposure to Hazardous Chemicals - Guide for Medical Practitioners. Book Health Monitoring for Exposure to Hazardous Chemicals - Guide for Medical Practitioners, City.

Stats NZ. (2020) Overseas merchandise trade datasets. Book Overseas merchandise trade datasets, City: Stats NZ.