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# Preliminary Assessment of Tunic Off-Gassing after Wildland Firefighting Exposure

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**Abstract:** Evidence has previously shown that outer tunics (turnout coats) worn by firefighters at structural fires are contaminated with harmful chemicals which subsequently off-gas from the material. However, there is limited research on whether this phenomenon extends to wildland firefighter uniforms. This pilot study aimed to explore if the tunics of volunteer bushfire and forestry firefighters in Western Australia off-gas any contaminants after exposure to prescribed burns or bushfires, and whether there is a need to explore this further. Nine tunics were collected from firefighters following nine bushfire and prescribed burn events, with a set of unused tunics serving as a control. Chemical analysis was performed on these tunics to assess levels of acrolein, benzene, formaldehyde, and sulphur dioxide contamination. The assessment involved measuring chemical off-gassing over a 12 h period using infrared spectrometry. Tunics worn by firefighters appear to adsorb acrolein, benzene, formaldehyde, and sulphur dioxide from bushfire smoke and these contaminants are emitted from firefighting tunics following contamination at elevated concentrations. Further investigation of this research with a larger study sample will be beneficial to understand this phenomenon better and to determine the full extent and range of chemical contaminants absorbed by all firefighter clothing.

**Keywords:** wildfire; bushfire; volunteer firefighter; forestry firefighter; smoke exposure; Western Australia; off-gassing; secondary exposure; tunic; personal protective equipment (PPE)



**Citation:** Padamsey, K.; Liebenberg, A.; Wallace, R.; Oosthuizen, J. Preliminary Assessment of Tunic Off-Gassing after Wildland Firefighting Exposure. *Fire* **2024**, *7*, 321. https://doi.org/10.3390/fire7090321

Academic Editor: David Bowman

Received: 8 July 2024
Revised: 22 August 2024
Accepted: 11 September 2024
Published: 14 September 2024



## 1. Introduction

Bushfires (wildfires) are an increasing threat across Australia. Fires burn more frequently and with increased intensity [1]. In Australia, this was evident during the 2019/20 bushfire season, commonly referred to as "Black Summer". Bushfires ravaged over ten million hectares of land, claiming the lives of nine firefighters and displacing thousands of people [2,3].

In Western Australia (WA), there are several firefighting services that primarily respond to wildland fire threats. The largest service is the volunteer Bushfire Service, with over 26,000 members, and more than 500 Brigades funded by local government authorities and managed by the Department of Fire and Emergency Services [4]. The Department of Biodiversity, Conservation and Attractions (DBCA) also operates and manages a paid firefighting force (hereafter referred to as forestry firefighters), responsible for managing the vast national parks of the State. Forestry firefighters respond to bushfires during the summer months and conduct prescribed burning campaigns in the cooler months. Both groups of firefighters wear similar protective uniforms consisting of fire-retardant turnout gear, tunic (outer coat) and bottoms, boots, helmets, eye, and respiratory protection [5]. The turnout gear is typically made from 100% Proban cotton, covering the firefighter from chin to waist, including the arms, designed to overlap with other personal protective equipment (PPE) such as gloves and pants, thus ensuring adequate full protection for the firefighter. All turnout gear worn by firefighters is certified to the Australian and New Zealand standard [6]. Prescribed burning is routinely undertaken where areas of the bushland are set

alight under the guidance of wildland firefighters. This management strategy is used to reduce dangerous fuel loads and mitigate bushfire risk. Prescribed burning is a delicate process, requiring a fine balance between environmental and meteorological conditions to meet a desired outcome. The term "prescribed burn" is often used to describe these fires as they follow a "prescription" in which the specific conditions must be met before ignition [7]. The DBCA Parks and Wildlife (DPAW) division outlines four primary purposes for prescribed burning, namely, to maintain biodiversity, to rehabilitate vegetation after acts such as timber harvesting and mining, to undertake research, and to assist in protecting lives and property from bushfire by reducing the build-up of hazardous fuel loads [7].

While attending bushfires or prescribed burn events, firefighters are frequently exposed to potentially harmful chemicals emanating from the burning vegetation [8,9]. Of the many chemicals present in bushfire smoke, previous research has highlighted the prevalence and negative health impacts associated with acrolein, benzene, sulphur dioxide, and formaldehyde exposure, either for their irritant properties or, crucially, their carcinogenic nature [10]. This pilot study focused on these four chemicals given that they are largely responsible for wildland firefighting being recently classified as a carcinogenic-exposed occupation [11,12].

Personal protective equipment (PPE) is a vital control used to protect firefighters from harmful exposures to airborne contaminants generated by fire. Respiratory protection equipment is particularly essential to prevent inhalation of these contaminants, while the firefighting tunic is primarily used to prevent against the heat generated by fire, but also to prevent dermal absorption of hazardous chemicals. However, this PPE could also present an additional exposure risk if the tunic becomes contaminated during firefighting events. Fent, et al. [13] and Banks, et al. [14] found that PPE worn by firefighters has the potential to adsorb contaminants from structural fires and, after the fire event, goes through a period of off-gassing when contaminants are released from the PPE into the surrounding atmosphere, indicating that a firefighters tunic could be a potential secondary source of exposure.

Previous research on wildland-related secondary exposure sources is limited as the focus has been on firefighter exposure to contaminants associated with burning human-made materials such as buildings or cars, often conducted under controlled experimental conditions [13]. Previous research was not conducted during live bushfire events, and as far as can be determined, there has been no further exploration of whether this contamination–off-gassing phenomenon is associated with chemicals from bushfires in Australia.

This pilot study aimed to explore if the tunics of volunteer bushfire and forestry firefighters in Western Australia off-gas any contaminants after exposure to prescribed burns or bushfires, and determine the need to further explore this phenomenon.

## 2. Materials and Methods

### *2.1. Particpants and Recuitment*

Between November 2022 and April 2023, the research team was invited by the DBCA to attend prescribed burns and bushfires for research purposes. Firefighters who attended these prescribed burns or bushfires were recruited for this study. Participants were recruited from two distinct groups:

- Volunteer Bushfire Firefighters: These firefighters were volunteers from a brigade located in metropolitan Perth (WA), and they attended bushfire events.
- Forestry Firefighters: These participants were forestry firefighters from the Department of Biodiversity, Conservation and Attractions (DBCA), and they attended the prescribed burns.

Potential participants were informed about the study by the principal investigator to gauge their initial interest, prior to commencing their shifts at the respective fire events. Firefighters who agreed to participate were provided with a participant information letter and given time to read this and ask any questions before providing written consent to participate in the research.

### 2.2. Assessment of Potential Tunic Contamination

Participants were included if they confirmed that their tunic (turnout coat) was clean, not worn prior to use on that shift and subsequently that they wore their tunics for a minimum of four hours while performing their usual duties at the fire events. Only firefighters fulfilling the "firefighter" role were included; drivers, crew leaders and non-frontline roles were excluded. The firefighter role includes responsibility for taking lines of hose to the fire front to combat the fire. One tunic from each fire event was collected from the firefighters and immediately placed in a plastic airtight 50 L sealed container. Due to the unpredictable and hazardous nature of wildland fires, it was not feasible to control the exact amount of smoke exposure each firefighter faced. We confirmed with firefighters at prescribed burns that they were not using drip-torches and observed only matches being used to ignite the burns, to limit the influence of the disease/petrol contamination on the tunics. Exposure at both bushfire events and prescribed burns lasted between 4 and 6 h and was confirmed by the participating firefighters to be typical of a regular shift and time spent in smoke.

### 2.3. Tunic Analysis

All tunics were analysed individually for potential off-gassing. The time taken to transport the tunic from the fire site to the temperature-controlled laboratory where testing took place ranged from one to four hours, contingent on the fire's location. The tunics were moved from the transport vessel into a sealed sterile 100 L plastic container for assessment, the same approximate size of the lockers that PPE is generally stored in at fire stations. The sterile containers were designed with an aperture in the lid to accommodate the probe of the Gasmet Technologies DX4040 Fourier transform infrared spectrometer (FTIR), Vantaa, Finland, which was sealed in place using a tight-fitting rubber stopper. The FTIR was previously calibrated and configured to measure the mean concentration of four chemicals—acrolein, benzene, formaldehyde, and sulphur dioxide—commonly found in bushfire smoke. These chemicals were selected due to their known irritant or carcinogenic properties, making them appropriate markers for determining health risk in wildfire environments. Additionally, these toxicants are frequently studied in wildland fire research, providing a basis for comparison and relevance to existing literature. The mean concentration of the four chemicals were measured at intervals of 5 min, over a period of 12 h. Following the 12 h sampling period, the individual tunics were cleaned using a standard domestic washing machine cycle and returned to the firefighters. This is consistent with the routine procedures for DBCA and DFES for cleaning turnout gear, which involves removing debris with a soft brush before machine-washing and air-drying after each use.

To establish a control sample for the experiment and to allow for comparison, three sets each of brand new and washed tunics were subjected to the same off-gassing analysis as the tunics worn and exposed at fire events.

## 3. Results

### 3.1. Fire Events

This study covered a total of nine fire events, comprising five prescribed burns and four bushfire events. The prescribed burns were conducted by the DBCA during spring 2022, in accordance with their 2022/23 fire mitigation prescription. The locations for these burns ranged from the Badgingarra Kwongan Heath (sandy heathland) in the north, known for its exceptional biodiversity, to the Wandoo woodlands of Julimar in the east, extending to the dense jarrah forests of Nannup in the south. The size of these prescribed burns varied from smaller 150-hectare burns in the southern forest regions to expansive burns covering over 1000 hectares in the eastern woodlands.

The bushfire events took place during the summer of 2022/23. Each of these events was a critical, uncontrolled emergency that required immediate intervention by volunteer firefighters. The bushfires varied in their intensity and duration, ranging from smaller

scrub fires that were extinguished within hours to large-scale multi-agency operations that lasted days. All bushfires occurred in the Perth metropolitan area.

This research explored both prescribed burns and bushfires due to their potential differences in fire intensity and firefighter tactics and strategies used to control these fires. These may impact the firefighter's exposure to smoke and affect their overall exposure profile.

### *3.2. Off-Gassing Analysis*

The findings suggest that tunics worn by firefighters during bushfires or controlled burn events potentially adsorb and appear to off-gas chemicals typically found in bushfire smoke. The following section will discuss the findings of the off-gassing analysis. Figures 1–4 display the mean concentration of chemicals measured in the container over the 12 h sampling period, as well as the highest mean concentration of chemicals measured for any 15 min sampling period. The results indicate that all three clean tunics off-gassed similar concentrations of chemicals; thus, the mean results of all three tunics are presented as a single item in the tables for comparison and simplicity. The contaminated tunics off-gassed the highest concentration of chemicals during the first 15 min of measurement reported as 15 min maximum concentrations (Figures 1–4).

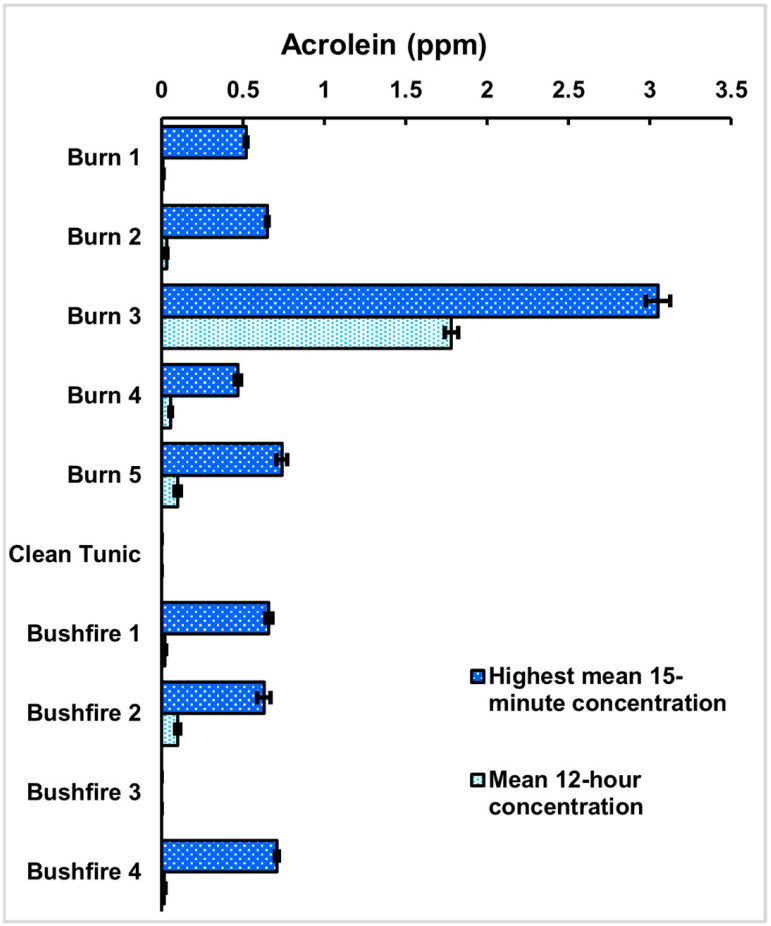


**Figure 1.** Summary of acrolein off-gassing from fire-fighting tunics.

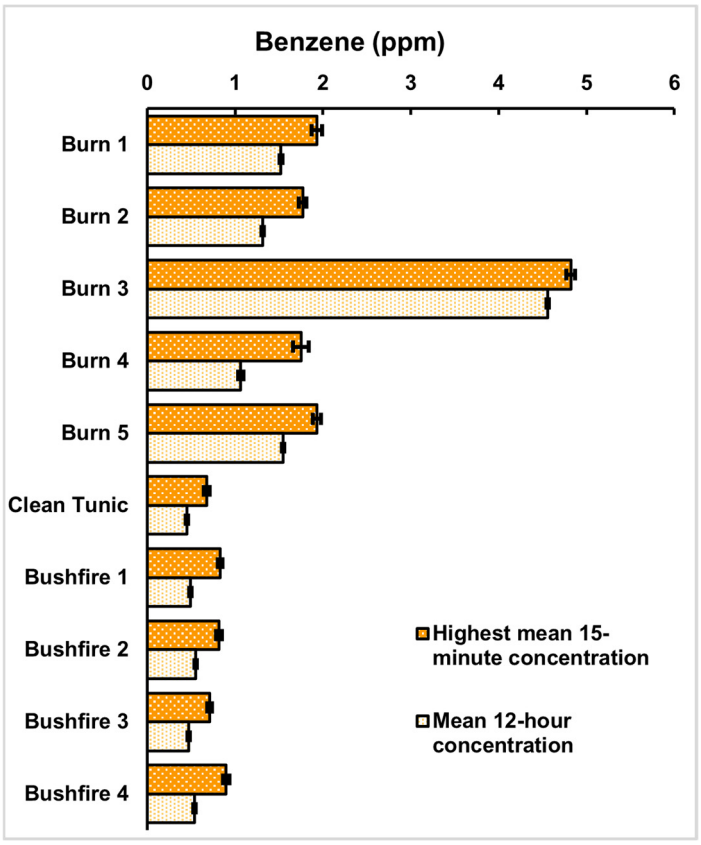


**Figure 2.** Summary of benzene off-gassing from firefighting tunics.

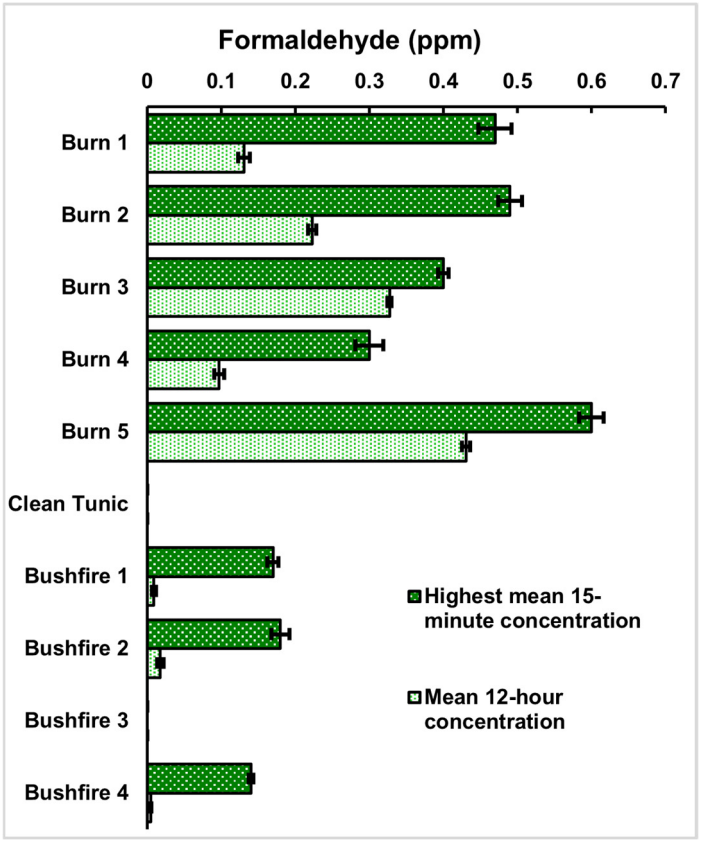


**Figure 3.** Summary of formaldehyde off-gassing from firefighting tunics.

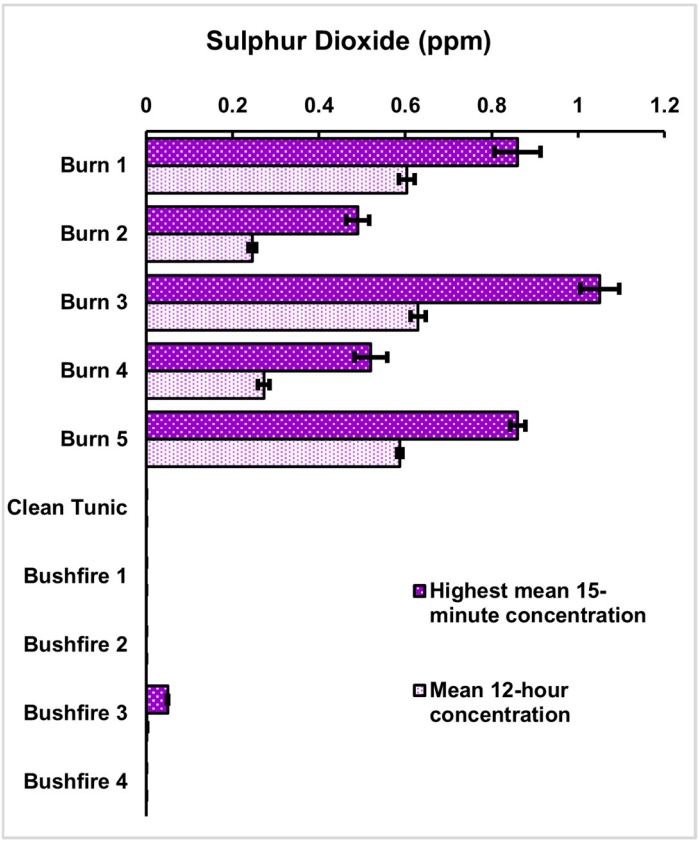


**Figure 4.** Summary of sulphur dioxide off-gassing from firefighting tunics.

#### 3.2.1. Acrolein

Tunics from both controlled burns and bushfires off-gassed acrolein at similar levels. For controlled burns, the average concentrations varied from 0.01 ppm (Burn 1) to 0.09 ppm (Burn 5). A notable deviation was recorded during Burn 3, where the mean acrolein concentration in the tunic was higher by comparison, at 1.78 ppm (Figure 1). The clean tunics did not appear to off-gas any acrolein.

#### 3.2.2. Benzene

The benzene concentrations released from tunics post bushfire events were consistent, ranging between 0.45 ppm and 0.55 ppm; a "clean" tunic—that had not been exposed to fire—also off-gassed benzene at levels comparable to those from bushfire-affected tunics. Conversely, tunics from controlled burns exhibited higher benzene off-gassing, with the third burn peaking at 4.82 ppm and an average release of 4.56 ppm (Figure 2).

#### 3.2.3. Formaldehyde

Tunics subjected to controlled burns displayed higher formaldehyde off-gassing concentrations than those from bushfires. Tunics exposed at prescribed burns showed a range from 0.097 ppm (Burn 4) to 0.431 ppm (Burn 5), while the highest mean concentration observed for bushfire tunics was 0.01 ppm (Figure 3). The clean tunics did not off-gas any detectable concentrations of formaldehyde.

#### 3.2.4. Sulphur Dioxide

Sulphur dioxide gas was primarily detected in tunics used during controlled burns, with mean off-gassing concentrations over a 12 h period ranging between 0.246 ppm and 0.630 ppm. In comparison, one tunic from Burn 3 emitted sulphur dioxide, reaching a 15 min maximum of 0.05 ppm (Figure 4). The clean tunics did not appear to off-gas any concentration of sulphur dioxide.

## 4. Discussion

The aim of this study was to explore if the tunics of volunteer bushfire and forestry firefighters in Western Australia are contaminated with chemicals after a wildland fire event and to what extent the tunic off-gasses these chemicals post fire. The results of this study suggest that this process may also occur during wildland fire events in the same manner as those reported from structural fire events [13,14]. It was observed that the tunics from controlled burns emitted higher concentrations of formaldehyde, benzene, and sulphur dioxide compared to those from bushfire incidents. The release of acrolein was comparable in garments used at both types of fires. The controls (clean tunics) were found to off-gas small concentrations of benzene similar to those concentrations observed at bushfire events, but the other gases were below the detectable limits of the FTIR. This process of possible off-gassing may present a secondary exposure source to firefighters and pose an additional health risk to consider for firefighting agencies.

### *4.1. Chemical Measurements and Associated Risks*

For the purposes of brevity, in this early investigation, we concentrated on four gases that were found in relatively high concentrations in bushfire smoke and have been focussed on in the literature previously [15]. These four gases were acrolein, benzene, formaldehyde, and sulphur dioxide. Safe Work Australia has stipulated workplace exposure standards (WESs) [16] for the chemicals tested. Although the WESs were designed for and applicable to personal exposure in workers, they do provide context for the chemical concentration levels found in this study. However, a direct comparison is not possible due to the strict methodology required for workplace exposure monitoring. Nonetheless, these standards may serve as an indication of when concern should be applied to the concentration levels found.

#### 4.1.1. Acrolein

For acrolein, the National Institute for Occupational Safety and Health (NIOSH) recommends a time-weighted average (TWA): the concentration not to be exceeded averaged over an 8 h shift of 0.1 ppm and a STEL (short-term exposure limit; the concentration not to be exceeded for a period of 15 min, more than four times over the duration of the shift) of 0.3 ppm [17]. Safe Work Australia also adopts a 0.1 ppm TWA and 0.3 STEL [16]. Figure 1 shows that across three of the four bushfires and all the prescribed burns, the tunic off-gassed acrolein for 15 min in concentrations above the STEL. The TWA was exceeded in three of the nine tunics measured. Acrolein is an unsaturated aldehyde commonly found in tobacco smoke and the combustion of wood, plastics, and petroleum [18]. It is a high relative electrophile which has been demonstrated to be active for several days in vivo [19]. Inhalation of acrolein has been shown to induce vascular [20], neurogenerative [21], and respiratory diseases [22]. Acrolein has also been linked to cancers, with evidence of malignant tumours in mouse models [23]. In 2020, the International Agency for Research on Cancer (IARC) classified acrolein as a class 2A (probable) carcinogen on the basis that sufficient evidence from animal experimental studies exists coupled with a strong mechanistic pathway [24]. Acrolein displays many properties of a carcinogen, namely, being genotoxic, inducing oxidative stress and chronic inflammation, and being immunosuppressive [24]. Other studies have confirmed the presence of acrolein in bushfire smoke and have identified it as a hazard to firefighters [10]; our findings suggest that the tunic may absorb acrolein and off-gas it in concentrations that may further impact the health of those exposed.

#### 4.1.2. Benzene

Benzene is an aromatic hydrocarbon which has historically been used in manufacturing and the petroleum industry, and is a by-product of combustion. NIOSH recommends a TWA of 0.1 ppm and a STEL of 1.0 ppm [25]. According to Safe Work Australia, benzene has a TWA of 1.0 ppm and no STEL [26]. Figure 2 shows that the NIOSH STEL was exceeded

with each tunic that was exposed at a prescribed burn. At prescribed Burn 3, this was exceeded by 355%. Levels of benzene were considerably lower in tunics exposed at bushfire events (all below 1.0 ppm). The NIOSH TWA was exceeded at every fire event. Benzene exhibits many characteristics of a carcinogen, being metabolically activated, genotoxic, inducing oxidative stress, causing haematotoxicity, and being immunosuppressive [27,28]. Since 1979, benzene has been classified as carcinogenic (IARC group 1) to humans based on significant evidence that demonstrates a causal pathway of leukaemia [29]. Since that time, several large cohort studies have demonstrated further associations between benzene and other cancers, such as mesothelioma, multiple myeloma, and non-Hodgkin lymphoma [30–32]. In 2017, the IARC finalised its evaluation of benzene as a carcinogen, classifying it as a group 1 carcinogen [27]. Benzene is a toxin known to exist in bushfire smoke [10,33]; this research study suggests that benzene exposure to firefighters may extend long after the completion of firefighting activities if the tunics of firefighters are not safely isolated.

#### 4.1.3. Formaldehyde

Formaldehyde or methanal is an important chemical with widespread industrial applications and it is also a by-product of natural and anthropogenic events such as bushfires, smoking tobacco, and burning petroleum-based fuels [34]. NIOSH recommends a maximum 15 min exposure of 0.1 ppm [35]. Safe Work Australia recently lowered the TWA workplace exposure level to 0.1 ppm and its STEL to 0.3 ppm [16]. Figure 3 shows that each tunic from the prescribed burn exceeded this exposure level, except for Burn 4, which recorded a 12 h average of 97% of the TWA and below the STEL. Acute exposure to formaldehyde in low concentrations, 0.1 to 5 ppm, has been shown to cause burning of the eyes, lacrimation, and general upper respiratory irritation [36]. It has also been shown to exacerbate allergic asthma and dermal allergies [37]. In 2006, the IARC classified formaldehyde as a carcinogen to humans, initially from evidence of increases in rare nasopharynx cancers prevalent among those exposed to the chemical [38]. There is growing evidence of formaldehyde being a risk factor for leukemia [34] and cancers of the nasal passage [39]. Research has demonstrated that bushfire smoke contains formaldehyde [10]; this research study presents new evidence that the exposure to this toxin may extend beyond the fire front and may also impact the health of those exposed.

#### 4.1.4. Sulphur Dioxide

Sulphur dioxide is a toxic gas and common air pollutant. Sulphur dioxide may be emitted through the burning of fossil fuels, industrial processes such as refining metal from ore, and from natural sources such as volcano eruptions [40]. The National Institute for Occupational Safety and Health [41] recommends a TWA of 2.0 ppm and a STEL of 5.0 ppm, which are also adopted by Safe Work Australia [16]. Figure 4 shows that at all fire events observed, the tunic did not off-gas sulphur dioxide in higher concentrations than the TWA or STEL. However, the cumulative effects of sulphur dioxide compared to the other chemicals observed could be a potential issue, especially considering the concentration of acrolein, benzene, and formaldehyde previously discussed. Short-term exposure to sulphur dioxide can affect the upper respiratory system, impeding the breathing of those exposed and causing irritation to the eyes. High concentrations of the gas may also form other sulphur oxides, reacting to other compounds in the air and forming small particles (PM), which can penetrate deep into the lower respiratory system and increase the risk of other health issues.

### *4.2. A Potential Secondary Exposure Risk*

Overall, there appears to be a consistent off-gassing of the chemical acrolein, benzene, formaldehyde, and sulphur dioxide from firefighting tunics after exposure at fire events. When worn after fire events, firefighters may be exposed to these chemicals due to the off-gassing process. These findings may be particularly important given that prior research has

revealed forestry firefighters often wear their contaminated PPE in their personal vehicles. Additionally, they tend not to launder their PPE regularly, and when this does occur, it is typically takes place at their home residences [5].

### *4.3. Cumulative Effects*

It may be important to account for the cumulative toxic effects of the chemicals released from tunics post fire, as well as the effects of each chemical individually. Additive effects between carcinogens are feasible [42], and the co-carcinogenic effects of chemicals within bushfire smoke may exacerbate the carcinogenic effect. This research suggests that, following a fire event, firefighters may face exposure to a variety of chemicals off-gassing from their PPE, each with its own health implications. The collective release of substances such as acrolein, formaldehyde, benzene, and sulphur dioxide—in addition to other chemicals not analysed in this study—could heighten the potential for health hazards. Moreover, continued exposure to these emissions, coupled with the physical and mental demands of firefighting, may lead to further health issues [43]. The interaction of these effects could potentially be more complex than additive; they might be multiplicative or synergistic, indicating that the overall risk from combined emissions could surpass the risks associated with each chemical individually [44]. Therefore, it is important to evaluate the potential collective impact of these exposures in future studies.

### *4.4. Strengths and Limitations*

This study provides early novel insights into the contamination of firefighters' tunics from bushfire incidents in Western Australia, creating a foundational dataset for subsequent investigations. Nonetheless, several limitations must be acknowledged: First, the sample size is limited, and no repeat measures were conducted at each fire. Future studies should aim to sample multiple tunics from a range of different fire scenarios. The assessment focused solely on four chemicals off-gassing from the tunics, whereas other chemicals may also be potentially harmful and also should be analysed. The contaminant (smoke) dosage received by each tunic was not quantified through personal exposure measurements. A more robust quantitative measure of exposure should be used in follow-up studies to ascertain exposure amount. Additionally, inadvertent contamination of the tunics from sources such as foam or vegetation-coated flame retardant may have influenced the results. The Gasmet DX4040 has theoretical lower detection limits of 0.25 ppm for acrolein, 0.13 ppm for benzene, 0.09 ppm for formaldehyde, and 0.03 ppm for sulphur dioxide, based on a one-minute sample duration. To improve the reliability of results at lower concentrations, we extended the sampling duration to five minutes. However, it is important to exercise caution when interpreting results that fall below these established detection limits, as they may be less accurate.

### *4.5. Recommendations and Future Research*

Our recommendation from this early research is to treat clothing worn during bushfire events as contaminated and potentially hazardous as demonstrated by research on structural fire events. Upon finishing their duties, firefighters should have the means to change out of and safely isolate at least their tunics within their vehicles for transport back to the station for cleaning.

Further research regarding this phenomenon of off-gassing after wildland fires may prove valuable and should perform the following:

- Conduct repeat analysis of multiple tunics from the same fire event.
- Investigate a larger array of chemicals.
- Investigate if other wildland chemical agents such as foam additives influence the off-gassing of tunics.
- Investigate the impact of laundering on the off-gassing phenomenon.
- Assess the potential breakthrough of chemical contamination to undergarments and the skin.

- Conduct biological monitoring pre and post event to determine if contaminants have been absorbed by individuals.

## 5. Conclusions

This pilot study found that, similar to structural fires, chemicals emitted from wildland fires appear to contaminate firefighting tunics. Post fire, these tunics off-gas harmful chemicals such as acrolein, formaldehyde, benzene, and sulphur dioxide. This off-gassing may unnecessarily expose firefighters to these toxic substances, extending health risks beyond the fireground. Given the potential implications for firefighter health and safety, further investigation into the extent and mechanisms of this off-gassing phenomenon is crucial.

**Author Contributions:** Conceptualization, K.P. and J.O.; methodology, K.P. and J.O.; formal analysis, K.P.; investigation, K.P.; writing—original draft preparation, K.P.; writing—review and editing, K.P., A.L., R.W. and J.O.; supervision, A.L., R.W. and J.O. All authors have read and agreed to the published version of the manuscript.

**Funding:** We acknowledge and appreciate the support of Natural Hazards Research Australia who have provided a scholarship and support to the primary author for this important research. This research was supported by an Australian Government Research Training Program (RTP) scholarship.

**Institutional Review Board Statement:** This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of EDITH COWAN UNIVERSITY (2022-03698-PADAMSEY) for studies involving humans on the 12 of September 2022.

**Informed Consent Statement:** Written informed consent was obtained from all subjects involved in this study.

**Data Availability Statement:** The data that support this study cannot be publicly shared due to ethical or privacy reasons and may be shared upon reasonable request to the corresponding author if appropriate.

**Acknowledgments:** We graciously acknowledge the contributions of the firefighters participating in this study and the Department of Fire and Emergency Services and the Department of Biodiversity, Conservation and Attractions for their support and collaboration.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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