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Evaluating the impact of occupational noise exposure on workplace fatal and nonfatal injuries in the U.S. (2006–2020)

Jie He, Lauren M. Smith, Abas Shkembi, Richard L. Neitzel *

Department of Environmental Health Sciences, School of Public Health, University of Michigan, Ann Abor, MI, 48109, USA

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ABSTRACT

Objectives: This study assessed the relationship between occupational noise exposure and the incidence of workplace fatal injury (FI) and nonfatal injury (NFI) in the United States from 2006 to 2020. It also examined whether distinct occupational and industrial clusters based on noise exposure characteristics demonstrated varying risks for FI and NFI.

Methods: An ecological study design was utilized, employing data from the U.S. Bureau of Labor Statistics for FI and NFI and demographic data, the U.S. Census Bureau for occupation/industry classification code lists, and the U.S./Canada Occupational Noise Job Exposure Matrix for noise measurements. We examined four noise metrics as predictors of FI and NFI rates: mean Time-Weighted Average (TWA), maximum TWA, standard deviation of TWA, and percentage of work shifts exceeding 85 or 90 dBA for 619 occupation-years and 591 industry-years. K-means clustering was used to identify clusters of noise exposure characteristics. Mixed-effects negative binomial regression examined the relationship between the noise characteristics and FI/NFI rates separately for occupation and industry.

Results: Among occupations, we found significant associations between increased FI rates and higher mean TWA (IRR: 1.06, 95% CI: 1.01–1.12) and maximum TWA (IRR: 1.10, 95% CI: 1.07–1.14), as well as TWA exceedance (IRR: 1.04, 95% CI: 1.01–1.07). Increased rates of NFI were found to be significantly associated with maximum TWA (IRR: 1.06, 95% CI: 1.04–1.09) and TWA exceedance (IRR: 1.03, 95% CI: 1.01–1.05). In addition, occupations with both higher exposure variability (IRR with FI rate: 1.49, 95% CI: 1.23–1.80; IRR with NFI rate: 1.40, 95% CI: 1.14–1.73) and higher level of sustained exposure (IRR with FI rate: 1.27, 95% CI: 1.12–1.44; IRR with NFI rate: 1.21, 95% CI: 1.05–1.39) were associated with higher rates of FI and NFI compared to occupations with low noise exposure. Among industries, significant associations between increased NFI rates and higher mean TWA (IRR: 1.05, 95% CI: 1.02–1.08) and maximum TWA (IRR: 1.06, 95% CI: 1.04–1.08) were observed. Unlike the occupation-specific analysis, industries with higher exposure variability and higher sustained exposures did not display significantly higher FI/NFI rates compared to industries with low exposure.

Conclusions: The results suggest that occupational noise exposure may be an independent risk factor for workplace FIs/NFIs, particularly for workplaces with highly variable noise exposures. The study highlights the importance of comprehensive occupational noise assessments.

1. Introduction

Occupational injuries impose significant health and economic burdens on workers across U.S. industries (Matticks et al., 1992; Ohajinwa et al., 2018). In 2007, approximately 5600 fatal injuries (FIs) and 8.5 million nonfatal injuries (NFIs) were reported, with estimated associated medical costs of $310 million and $46 billion, respectively, while estimated indirect costs that year, including lost earnings and fringe benefits, amounted to nearly $192 billion (Leigh, 2011). In 2022, the number of FIs was still about 5500 (Bureau of Labor Statistics, 2023a), while NFI cases were down to about 3.5 million (Bureau of Labor Statistics, 2023b).

Occupational noise exposure is a pervasive hazard that impacts millions of workers globally. In the U.S., an estimated 25% of the workforce across various industries, approximately 39 million workers, are exposed to occupational noise (Kerns et al., 2018). Exposure to high occupational noise levels has been linked to numerous auditory and non-auditory health effects, such as noise-induced hearing loss (Le et al.,

* Corresponding author. Department of Environmental Health Sciences, School of Public Health, University of Michigan – Ann Abor, MI, 48109, USA.
E-mail address: rneitzel@umich.edu (R.L. Neitzel).

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2017; Tak and Calvert, 2008), tinnitus (Fredriksson et al., 2015), and cardiovascular disease (Dzhambov and Dimitrova, 2016; Tomei et al., 2010).

In addition to the health effects, noise exposure was found to exacerbate the risk of workplace injuries(Dzhambov and Dimitrova, 2017). The mechanism for this is not well understood. Some authors suggest that noise exposure can adversely affect workers' cognitive performance (Liebl and Jahncke, 2017), leading to distraction, reduced situational awareness (Lichenstein et al., 2012; Smith, 1990; Wilkins and Action, 1982), and increased mental workload (Shkembi et al., 2022b), which may result in human errors (Brammer and Laroche, 2012). Finally, increased fatigue and human errors were found to be associated with a higher risk of occupational injury (Arlinghaus et al., 2012; Kim and Jeong, 2020; Swaen et al., 2003).

While the relationship between noise exposure and workplace injuries has been explored, gaps remain in understanding the intricate relationship between the two (Shkembi et al., 2022b). For instance, adverse effects of noise exposure on work safety and injury probability have been noted, but primarily in studies that were limited by their cross-sectional nature (Amjad-Sardrudi et al., 2012). Similarly, while dose-response associations have been proposed, with risk generally noted to increase at average exposure levels between 85 and 88 dBA (Shkembi et al., 2022a; Yoon et al., 2015), the quality of evidence remains low, warranting a cautious interpretation of this association (Dzhambov and Dimitrova, 2017). Most studies of noise and injury risk have focused on either average exposure levels or specific industries or occupations, thereby limiting their generalizability.

To further understand the relationship between noise exposure and occupational injuries, this study sought to answer three key questions: (1) How do different noise metrics relate to injuries in occupational settings? (2) Are there natural clusters of occupations or industries that exhibit specific noise exposure characteristics? (3) Do certain clusters of occupations or industries, based on their noise exposure characteristics, have higher risk of injury?

This study was conducted to provide a national-scale evaluation of the relationship between noise exposures and occupational injuries in the U.S. between 2006 and 2020 by exploring the contributions of four different noise metrics. We hypothesized that (1) industries and occupations with higher mean Time-Weighted Average (TWA) noise levels, higher maximum TWA levels, greater noise variability, and a higher percentage of work shifts exceeding 85 or 90 dBA would exhibit higher FI/NFI rates; (2) there exist distinct clusters of occupations or industries based on their noise exposure characteristics; and (3) clusters of occupations or industries with different noise exposure profiles have different risks of FI/NFI.

2. Material and methods

2.1. Data collection

In this ecological study, we utilized comprehensive data sources derived from the U.S. Bureau of Labor Statistics (BLS), the U.S. Census Bureau (Census), Occupational Safety and Health Administration (OSHA), Mine Safety and Health Administration (MSHA), and the U.S./Canada Occupational Noise Job Exposure Matrix (NoiseJEM) (University of Michigan, 2024)developed at the University of Michigan. By employing data from NoiseJEM, OSHA, and MSHA, we compiled 367,092 occupational noise measurements from 2006 to 2020, adhering to the standards of the OSHA Permissible Exposure Limit (PEL) and Action Level (AL), which are identical to the PEL and AL used by MSHA. These measurements were categorized by the Standard Occupational Classification (SOC) 2010 and North American Industry Classification System (NAICS) 2012 codes, using methods we have described previously (Roberts et al., 2018).

In conjunction with noise exposure data, we included work-related NFIs and illness rates per 10,000 full time equivalent (FTE), as well as annual number of FIs, across various occupations and industries from the BLS Survey of Occupational Injuries and Illnesses (Bureau of Labor Statistics, 2021a) and Census of Fatal Occupational Injuries (Bureau of Labor Statistics, 2023c) reports during the same time frame. FTE is a standardized unit that converts the work of part-time staff into the equivalent number of full-time workers, ensuring that the NFI and illness rates are comparable even if the actual hours worked vary. For the purpose of focusing on injuries, we picked out the following set of specific NFI types due to their presumed association with noise: fractures; cuts, lacerations, punctures; bruises, contusions; heat burns; chemical burns; and amputations.

We included demographic data on the employed population, covering number of employed persons by different groups of age, sex, and race/ethnicity among occupations and industries, from the BLS Current Population Survey (Bureau of Labor Statistics, 2021b). Specifically, age data were the number of employed persons among groups categorized into 10-year intervals from 16 to 65 years and over. Sex and race/ethnicity data were the number of employed persons among groups categorized into following groups: women; Asian; Black or African American; Hispanic or Latino. Annual working hours by occupation and industry from the BLS' Occupational Employment and Wage Statistics (Bureau of Labor Statistics, 2023d) and Office of Productivity and Technology (Bureau of Labor Statistics, 2023e) were also included.

To maintain consistency and facilitate the data preprocessing, code lists for SOC (2018, 2010, 2000) and NAICS (2017, 2012, 2007, 2002) were downloaded from the Census website (Census Bureau, 2022).

2.2. Data preprocessing and manipulation

Fig. 1 presents a comprehensive overview of the data preprocessing flow of this study. For this study, we encountered datasets where demographic and certain FI data were not directly annotated with SOC/NAICS codes but only had descriptive titles. To integrate these datasets into our analysis, we matched the missing SOC/NAICS codes using existing code lists based on shared descriptive titles through R software.

Given the span of our datasets from 2006 to 2020 and the evolution of SOC/NAICS versions during this time, combined with the fact that NoiseJEM data lacked detail at finer SOC/NAICS levels, we identified that classification codes were stable over time at the minor SOC level (N = 93 for SOC, 2000, N = 94 for SOC, 2010, N = 95 for SOC, 2018, not accounting for "55-0000 Military Specific Occupations") and NAICS subsector level (N = 100 for NAICS, 2002; N = 99 for NAICS, 2007; NAICS, 2012; NAICS, 2017). This allowed us to aggregate the data meaningfully while retaining significant numbers of occupational noise measurements. Thus, we aggregated all the data to the SOC minor level and NAICS subsector levels by years, respectively.

For the demographic data, we summed the counts of employees across all the levels below minor/subsector level up to the minor/subsector levels for each demographic group (i.e., age, sex, and race/ethnicity) annually. Then we summed the number of employees for age groups above 45 years old across all the minor/subsector levels as one age group (age >45 years old). For each of all the minor/subsector levels, we converted the number of employees of demographic groups of women, Asian, Black or African American, Hispanic or Latino, and age >45 years old to percentage by dividing by the total number of employees.

For NFI data, we first consolidated working hours and then computed the number of injuries using the equation:

$$\text{Annual nonfatal injury counts} = \frac{\text{Nonfatal injury rate per } 10,000 \text{ FTE}}{20,000,000\text{h}} \times \text{Annual working hours} \tag{1}$$

Where 20,000,000 h is used as a normalization factor corresponding to the total number of hours worked by 10,000 FTE employees in one year,

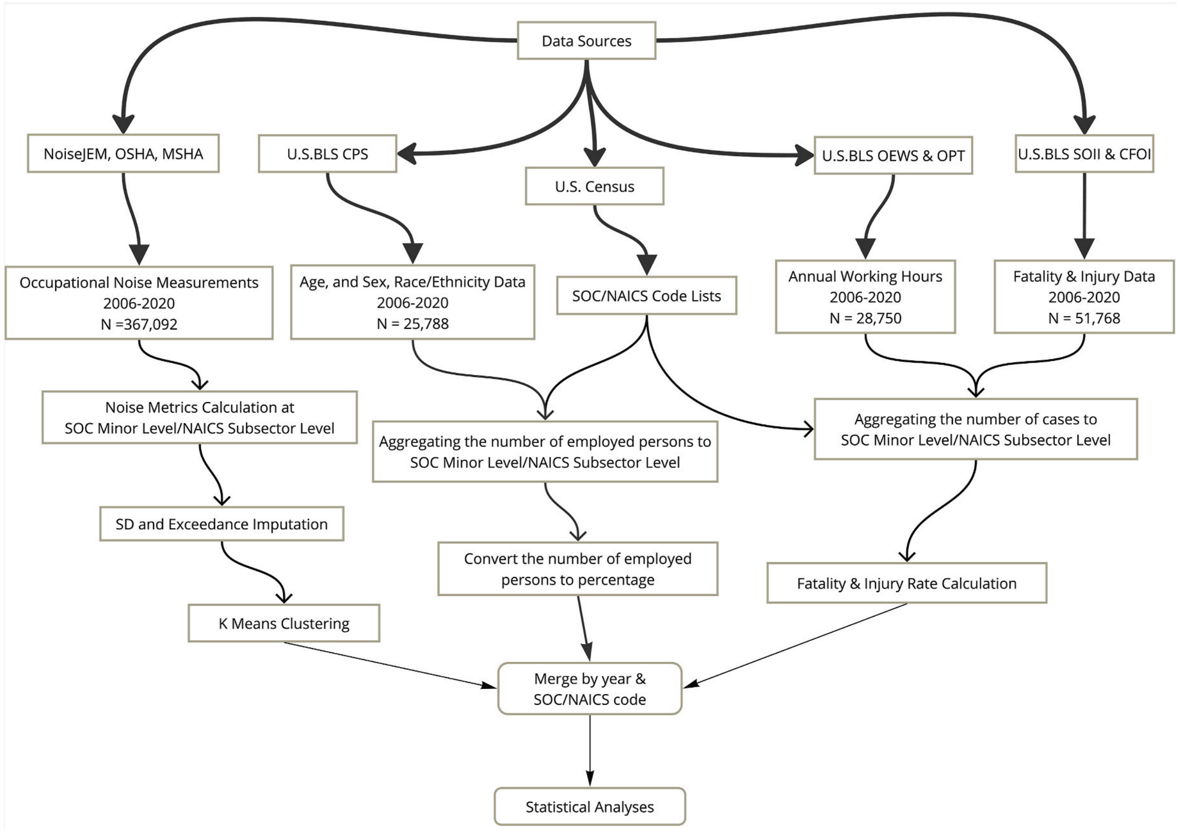

Fig. 1. Data Preprocessing Flow Chart.
Notes: This figure outlines the steps involved in preprocessing diverse datasets from 2006 to 2020.
Abbreviations: NoiseJEM: Noise Job Exposure Matrix; OSHA: Occupational Safety and Health Administration; MSHA: Mine Safety and Health Administration; BLS: Bureau of Labor Statistics; CPS: Current Population Survey; OEWS: Occupational Employment and Wage Statistics; OPT: Office of Productivity and Technology; SOII: Survey of Occupational Injuries and Illnesses; CFOI: Census of Fatal Occupational Injuries; SOC: Standard Occupational Classification; NAICS: North American Industry Classification System; SD: Standard Deviation.

assuming a 40-h workweek over 50 weeks. Annual working hours is the total number of hours worked by all employees in the organization over one year.

Subsequently, we aggregated the number of FI and NFI to the minor/subsector level for each year and converted it into rates to facilitate statistical analysis using following equations:

$$\text{Nonfatal injury rate per } 10,000 \text{ FTE} = \frac{\text{Annual nonfatal injury counts}}{\text{Annual working hours}} \times 20,000,000\text{h} \tag{2}$$

$$\text{Fatal injury rate per } 10,000 \text{ FTE} = \frac{\text{Annual fatal injury counts}}{\text{Annual working hours}} \times 20,000,000\text{h} \tag{3}$$

For noise measurements, we calculated four annual noise exposure metrics based on the measurements (work shift level) contained within each minor/subsector group for each year. Specifically, we calculated the annual mean 8-h TWA, standard deviation (SD) of TWA, maximum TWA, and TWA exceedances (the percent of work shifts >85 and >90 dBA by OSHA/MSHA AL and PEL, respectively). To calculate annual TWA exceedance, we first converted the measurement of each work shift to a binary variable (i.e., 0 for work shifts below the AL or PEL, and 1 for those above these limits), and then calculated the mean of the count of 1's out of all values at the minor/subsector level per year to get the percent of exceedance.

Although the noise data contains many measurements, upon aggregation at the minor/subsector level for each year, there was only a single noise measurement for 18% of occupation-years (N = 119 of total 638) and 9% of industry-years (N = 52 of total 636), thus hindering the calculation of SD of TWA and representation of TWA exceedance. To address this, we applied imputation, as detailed in section 1 of the **Supplementary Methods**. Following imputation, we utilized the k-means clustering algorithm on occupation/industry-years to differentiate clusters within occupations and industries based on the four noise metrics. The optimal number of clusters was ascertained through the elbow and average silhouette methods (Rousseeuw, 1987). The algorithm's performance metrics and specific clustering outcomes are detailed in Supplementary Figs. S4–S9. We ended up recognizing the following three clusters: Cluster 1, characterized by the lowest levels of all noise metrics and representing 'low exposure'; Cluster 2, 'volatile high exposure', marked by significant variability and higher maximum noise levels; and Cluster 3, 'constant high exposure', which consistently exhibits elevated mean, maximum, and exceedance levels with less variability.

Finally, we merged the datasets of noise metrics, demographics, and FI/NFI by year and SOC/NAICS code for statistical analysis. We ended up having 619 occupation-years and 591 industry-years for noise measurements made using OSHA/MSHA AL and 640 occupation-years and 625 industry-years for OSHA/MSHA PEL noise measurements from 2006 to 2020, out of a possible 1397 occupation-years and 1367 industry-years.

2.3. Statistical analyses

All data preprocessing and statistical analyses were performed using

R Statistical Software (R Core Team, 2021). For descriptive analyses of noise metrics and FI/NFI rates by occupation and industry, we calculated median and interquartile range (IQR), as appropriate. We employed mixed-effects negative binomial regression models via the glmmTMB R package (Brooks et al., 2017) to assess the relationship between noise and FI/NFI. K-means clustering algorithm was implemented through the cluster R package (Maechler et al., 2022). The two-sided threshold for statistical significance was p-value <0.05.

The primary predictors in our analysis were the four noise metrics (mean, SD, maximum, and exceedance), while the outcomes were either FI or NFI rates, the latter encompassing total NFIs or specific types of NFIs (e.g., lacerations). Each model was adjusted for the percentage of employees of demographic groups (women, Asian, Black or African American, Hispanic or Latino, age >45 years old). Given that the outcome variables were overdispersed count data, with the variance exceeding the mean, and that some outcomes—specifically amputations, chemical burns, and heat burns—exhibited zero-inflation (primarily due to data entries marked as 'data do not meet publication guidelines' and treated as zeros), a negative binomial regression model was utilized. The negative binomial model is particularly suited for handling over-dispersion, which in this case is exacerbated by the presence of excess zeros, thereby providing a robust analysis across all outcomes. Furthermore, since our data spanned multiple years and major occupation/industry groups, we introduced random intercepts for years and occupation and industry major groups and present results for unadjusted and demographic adjusted models.

The same models were performed again using the cluster labels from the k-means clustering as the exposure variable (instead of individual noise metrics) to examine the relationship between clusters and FI/NFI rates. Our objective was to determine whether the constant high exposure cluster and the volatile high exposure cluster exhibited increased Incidence Rate Ratios (IRRs) for FIs and NFIs compared to the low exposure cluster.

To evaluate the robustness of our regression analyses and better ensure the generalizability of the findings between noise exposure and FI/NFI rates across the broader spectrum of workplaces, we conducted sensitivity analyses for regression models, as described in section 2 of **Supplementary Methods**.

Due to the stronger indicators presented by AL noise metrics and clusters, we displayed these results here and included the results concerning PEL in the Supplementary Tables S1–S15 (odd-numbered). Additionally, for better visualization we displayed figures of regression results and included tables of unadjusted and adjusted models and sensitivity analyses in the Supplementary Tables S2–S14 (even-numbered). This approach prioritizes the most relevant findings and ensures a focused discussion on the observed trends and their implications for occupational health.

3. Results

3.1. Descriptive analyses

Descriptive statistics are reported in Table 1. Occupation level analysis included 619 occupation-years with a median of mean TWA of 83.7 (IQR: 9.8) dBA. The low exposure cluster (N = 145) had a notably lower median of mean TWA (75.7; IQR: 7.7) compared to the constant high exposure cluster (N = 231, median 89.6 (IQR: 5.0)) dBA. The SD of TWA, a measure of variability, was highest in the volatile high exposure cluster (N = 243), with a median of 9.2 (IQR: 2.9) dBA. TWA exceedances were frequent across the sample, with an overall median of 40.0% (IQR: 48.6). However, there were stark differences among the clusters, with low exposure occupations having a median of only 4.0% (IQR: 17.8) exceedance, and the constant high exposure cluster having a median of 78.6% (IQR: 36.8) exceedance. The median FI rate per 10,000 FTE was 0.25 (IQR: 0.69) across all occupations, with the lowest rate (0.10; IQR: 0.40) in the low exposure cluster and the highest rate (0.49; IQR: 1.05) in the volatile high exposure cluster. The median NFI rate across occupations was 30.46 per 10,000 FTE (IQR: 43.60), whereas the constant high exposure cluster demonstrated a median NFI rate of 36.22 (IQR: 38.40). Specific types of NFIs displayed variability across clusters. Fractures (median: 8.33; IQR: 11.34), cuts, lacerations, and punctures (median: 8.88; IQR: 18.62), and bruises and contusions (median: 8.20; IQR: 8.91) were the most common injuries, with the highest rates found within the volatile and constant high exposure clusters.

Similar trends were observed within industries (N = 591 industry-

Table 1
Characteristics of noise exposure metrics (AL (dBA)) and injury rates (per 10,000 FTE).

Variable	Overall	Low	Volatile High	Constant High
	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
Among Occupation	N = 619	N = 145	N = 243	N = 231
Mean (dBA)	83.7 (9.8)	75.7 (7.7)	82.4 (5.7)	89.6 (5.0)
SD (dBA)	7.1 (3.4)	6.8 (3.2)	9.2 (2.9)	5.7 (2.8)
Maximum (dBA)	93.5 (14.4)	82.8 (10.0)	96.1 (13.1)	97.2 (11.2)
Exceedances (%)	40.0 (48.6)	4.0 (17.8)	35.7 (23.6)	78.6 (36.8)
Fatal injury	0.25 (0.69)	0.10 (0.40)	0.49 (1.05)	0.22 (0.55)
Nonfatal injury	30.46 (43.60)	17.00 (28.10)	36.90 (43.11)	36.22 (38.40)
Fractures	8.33 (11.34)	5.70 (7.00)	11.64 (13.19)	8.55 (9.03)
Cuts, lacerations, punctures	8.88 (18.62)	3.20 (9.25)	10.52 (17.80)	12.74 (21.85)
Bruises, contusions	8.20 (8.91)	5.20 (7.81)	9.00 (10.30)	8.50 (6.70)
Heat burns	0.50 (1.60)	0.00 (0.45)	1.00 (2.00)	0.61 (2.60)
Chemical burns	0.10 (0.80)	0.00 (0.10)	0.30 (1.00)	0.20 (0.81)
Amputations	0.20 (1.30)	0.00 (0.20)	0.40 (1.50)	0.80 (2.20)
Among Industry	N = 591	N = 115	N = 236	N = 240
Mean (dBA)	87.2 (7.1)	80.8 (5.0)	86.3 (4.8)	90.7 (3.3)
SD (dBA)	6.3 (3.1)	5.0 (3.7)	7.5 (2.5)	4.9 (3.0)
Maximum (dBA)	96.0 (11.9)	85.7 (7.2)	98.5 (9.7)	98.7 (10.1)
Exceedances (%)	66.7 (41.9)	20.0 (33.3)	60.0 (23.2)	89.3 (19.0)
Fatal injury	0.28 (0.49)	0.24 (0.43)	0.27 (0.55)	0.29 (0.44)
Nonfatal injury	36.00 (23.30)	31.60 (23.30)	35.90 (20.26)	40.30 (26.20)
Fractures	10.21 (7.59)	9.31 (6.40)	10.31 (7.90)	11.00 (7.41)
Cuts, lacerations, punctures	11.30 (8.59)	9.60 (7.58)	11.80 (9.10)	11.90 (8.66)
Bruises, contusions	8.40 (7.70)	7.80 (10.37)	7.90 (5.41)	9.70 (8.35)
Heat burns	1.00 (1.70)	0.59 (1.40)	1.10 (1.44)	1.20 (2.15)
Chemical burns	0.40 (0.80)	0.20 (0.60)	0.40 (0.81)	0.40 (0.99)
Amputations	0.80 (1.79)	0.40 (1.10)	1.00 (1.70)	1.00 (2.17)

Notes: Table 1 presents the descriptive analysis of AL noise metrics alongside the rates of fatal and nonfatal injury, and specific nonfatal injury types, all per 10,000 FTE workers, across occupations and industries classified into low, volatile high, and constant high exposure clusters using data from 2006 to 2020.
Abbreviations: AL = Action Level; dBA = A-weighted decibels; SD = Standard Deviation; FTE = Full Time Equivalent; IQR = Interquartile Range.

years), where the median of mean TWA for the overall sample was 87.2 (IQR: 7.1) dBA. Here, the constant high exposure cluster (N = 236) had the highest median of mean TWA of 90.7 (IQR: 3.3) dBA, while the low exposure cluster (N = 115) exhibited a median of mean TWA of 80.8 (IQR: 5.0) dBA. TWA exceedances was strikingly high at a median of 66.7% (IQR: 41.9) across industries, with the constant high cluster having a median 89.3% (IQR: 19.0) of exceedances, reflecting the elevated risk in these environments. The FI rates within industries did not demonstrate significant variability, with a median of 0.28 per 10,000 FTE (IQR: 0.49) observed. However, NFI rate varied, with a median of 36.00 per 10,000 FTE (IQR: 23.30) reported overall, and the highest median NFI rate of 40.30 (IQR: 26.20) within the constant high exposure cluster.

3.2. Regression analysis with noise metrics and injury rates

The results of the unadjusted and adjusted models are displayed in Supplementary Table S2 and Fig. 2 (also in Supplementary Table S6), respectively.

3.2.1. Associations among occupations

The analysis among occupations, encompassing 619 occupation-years, revealed that a doubling (an increase of 5 dB according to OSHA/MSHA) in the mean TWA correlates with a 6% higher FI rate (incidence rate ratio (IRR): 1.06, 95% CI: 1.01–1.12). For each 5 dB increase in the maximum TWA, the FI rate increased by 10% (IRR: 1.10, 95% CI: 1.07–1.14). The exceedance also exhibited substantial effects, with every 10% increase in exceedances being associated with a 4% increase in FI rates (IRR: 1.04, 95% CI: 1.01–1.07).

NFI rates among occupations did not demonstrate a significant association with mean TWA (per 5 dB IRR: 1.03, 95% CI: 0.99–1.06), although they did for maximum TWA (per 5 dB IRR: 1.06, 95% CI: 1.04–1.09). This trend was also observed across specific NFI types, with the strongest association observed in amputations (IRR: 1.28, 95% CI: 1.18–1.39). In addition, every 10% increase in exceedance was associated with a 3% increase in FI rates (IRR: 1.03, 95% CI: 1.01–1.05).

3.2.2. Associations among industries

Among industries, with 591 industry-years analyzed, the IRR for FI rates indicated no significant association with the mean TWA, although it did for NFI rates. Each doubling (5 dB increase) in mean TWA was associated with a 5% increase in NFI rates (IRR: 1.05, 95% CI: 1.02–1.08). The association with maximum TWA was consistent with those among occupations, indicating a 6% higher NFI rates for every 5 dB increase (IRR: 1.06, 95% CI: 1.04–1.08). The relationships between maximum TWA exposure and specific types of NFIs were consistent with those among occupations, except for the chemical burns (IRR: 1.09, 95% CI: 1.00–1.20).

3.2.3. Comparison between unadjusted and adjusted models

The unadjusted and adjusted model results among occupations showed similar patterns overall. However, the associations between

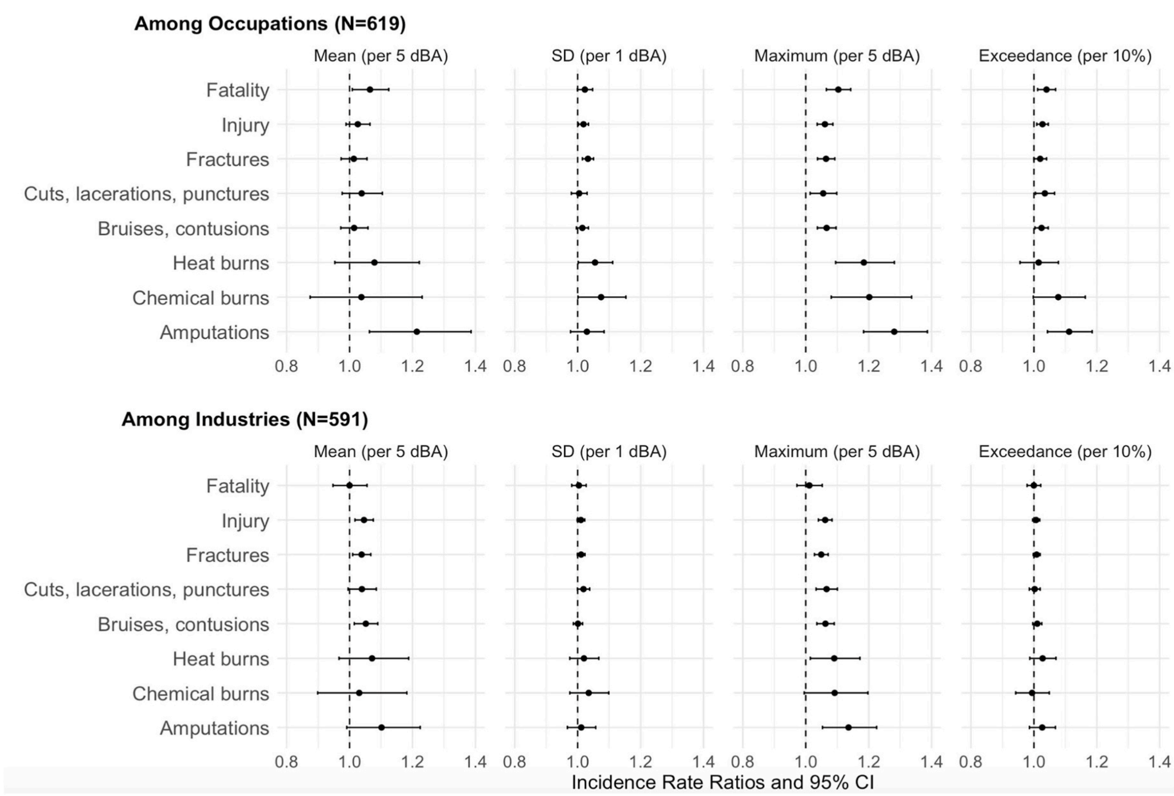

Fig. 2. Incidence Rate Ratios of Injuries Associated with AL Noise Metrics among Occupations and Industries.

Notes: This figure presents the results from a mixed-effects negative binomial regression model estimating the association between noise metrics using OSHA/MSHA AL standard and injury rates per 10,000 FTE, adjusted for age, sex, race, and ethnicity. Additionally, the model includes year as a random intercept to account for temporal variations, as well as NAICS sector level code for industry and SOC major level code for occupation as random intercepts, to address clustering within industries and occupations. The estimates are presented as Incidence Rate Ratios (IRRs) with their 95% confidence intervals (CIs). An IRR greater than 1 indicates an increased injury rate associated with each unit increase in noise metrics. Specifically, one unit increment refers to 5 dBA for mean and maximum TWA, 1 dBA for SD of TWA, and 10% for TWA exceedance.

Abbreviations: SD = Standard Deviation; AL = Action Level; OSHA = Occupational Safety and Health Administration; MSHA = Mine Safety and Health Administration; TWA = Time-weighted Average; SOC = Standard Occupational Classification; NAICS = North American Industry Classification System; dBA = A-weighted decibels; FTE = Full Time Equivalent.

mean TWA and exceedance with FI rates among occupations changed from null to significant with adjustments, implying that demographic variables may have obscured true effects. In addition, for some specific types of NFI rates among occupations/industries, we found that their associations with mean TWA, SD of TWA and exceedance become insignificant with adjustments, which might indicate that these associations were confounded by demographic variables.

3.3. Regression analysis with clusters and injury rate

The results of unadjusted model and adjusted model were displayed in Supplementary Table S4 and Fig. 3 (also in Supplementary Table S8), respectively.

3.3.1. Associations among occupations

Among occupations (N = 619) the volatile high exposure cluster was associated with a significantly increased FI rate (IRR 1.49, 95% CI: 1.23–1.80) compared to the low exposure cluster reference. Similarly, the constant high exposure cluster also showed a heightened FI rate with an IRR of 1.40 (95% CI: 1.14–1.73). When examining NFI rates, the volatile high and constant high exposure clusters also demonstrated significant associations (IRR: 1.27, 95% CI: 1.12–1.44; IRR: 1.21, 95% CI: 1.05–1.39) compared to the low exposure cluster. Specific NFI types among occupations showed increased rates in the volatile high exposure cluster, with chemical burns showing a notably high IRR of 3.51 (95% CI: 2.05–6.04) compared to the low exposure cluster. The constant high exposure cluster was associated with a substantial increase in rates of fractures, cuts, lacerations, punctures, and chemical burns, with IRRs of 1.22 (95% CI: 1.05–1.41), 1.28 (95% CI: 1.01–1.61), and 2.19 (95% CI: 1.23–3.92), respectively, compared to the low exposure cluster. In addition, when using the constant high exposure cluster as the reference, we found no significant associations between the volatile high exposure cluster and the rates of NFI or FI.

3.3.2. Associations among industries

Among industries (N = 591), the patterns of association were less pronounced. The volatile high and constant high clusters did not demonstrate a statistically significant increase in FI rates when compared to the low exposure cluster. However, NFI rates showed a positive, non-significant increase in the volatile high (IRR: 1.06, 95% CI: 0.97–1.15) and constant high (IRR: 1.09, 95% CI: 1.00–1.15) exposure clusters. Specific NFI types such as fractures had a slightly elevated risk in both the volatile high and constant high exposure clusters, showing IRRs of 1.06 (95% CI: 0.97–1.22) and 1.09 (95% CI: 1.00–1.19), respectively. Chemical burns did not show a significant increase in IRRs compared to the reference group among industries. Furthermore, no significant associations were observed between the volatile high exposure cluster and the rates of NFI or FI, when compared to the constant high exposure cluster used as the reference.

3.3.3. Comparison between unadjusted and adjusted models

Among occupations, the association between the cluster of constant high exposure and amputations rate compared to low exposure cluster changed from significant to null after including adjustments, suggesting that demographic variables may have confounded the initial association. The associations for both high exposure clusters and fractures rate changed from null to significant after adjusting demographic variables, indicating that the demographic variables may have masked true effects

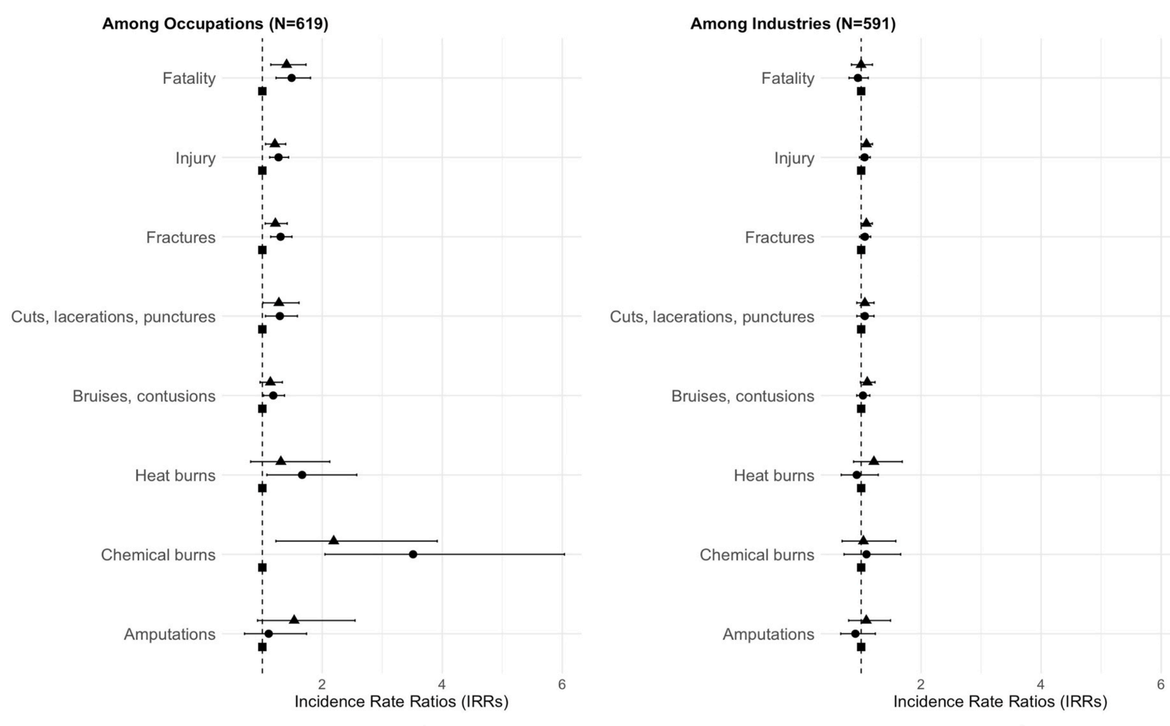

Fig. 3. Incidence Rate Ratios of Injuries Associated with AL Clusters among Occupations and Industries.
Notes: This figure presents the results from a mixed-effects negative binomial regression model estimating the association between clusters using OSHA/MSHA AL standard and injury rate per 10,000 FTE, adjusted for age, sex, race, and ethnicity. Additionally, the model includes year as a random intercept to account for temporal variations, as well as NAICS sector level code for industry and SOC major level code for occupation as random intercepts, to address clustering within industries and occupations. The estimates are presented as Incidence Rate Ratios (IRRs) with their 95% confidence intervals (CIs). An IRR greater than 1 indicates an increased injury rate associated with the cluster compared to low exposure cluster.
Abbreviations: SD = Standard Deviation; AL = Action Level; OSHA = Occupational Safety and Health Administration; MSHA = Mine Safety and Health Administration; TWA = Time-weighted Average; SOC = Standard Occupational Classification; NAICS = North American Industry Classification System; dBA = A-weighted decibels; FTE = Full Time Equivalent.

initially. Among industries, potential confounding effects were found as all the significant correlations became insignificant after adjusting for demographic variables.

3.4. Sensitivity analyses

The sensitivity analysis aimed to test the robustness of the adjusted model regression findings (Figs. 2 and 3). The results are described in Supplementary Tables S12, S14, and S16. Neither the exclusion of specific high-risk industry and occupations nor the inclusion of hazardous occupational conditions substantially altered the overall patterns observed in the original analysis.

4. Discussion

This study addresses a critical gap in the literature by exploring the relationship between occupational noise exposure and the incidence of FI and NFI in the workplace. The findings underscore that noise exposure, traditionally recognized for its auditory and non-auditory health effects, also constitutes a substantial safety concern. Using an ecological study design, we leveraged an extensive dataset spanning 15 years to examine these associations. Our first hypothesis was confirmed with the results that, among occupations, higher maximum TWA and TWA exceedance were associated with an increased risk of both FIs and NFIs while higher mean TWA was associated with higher risk of FIs only. Among industries, higher mean TWA and maximum TWA were associated with higher NFI risk only. Further, we hypothesized that specific clusters of noise exposure not only exist but could also be associated with different risks for occupational FIs and NFIs. Our analysis revealed that such clusters exist and were associated with disproportionate risk. Occupations with volatile high exposure (i.e., greater exposure variability, and higher maximum TWA) and constant high exposure (i.e., greater overall exposure level with low variability) demonstrated markedly higher rates of FIs and NFIs compared to low exposure. These findings underscore the critical need to recognize and address the differentiated impact of noise exposure across various occupations.

Our findings concur with existing literature on the effects of occupational noise on worker health and safety. For instance, a study of U.S. aluminum manufacturing workers reported a 21% escalation in NFI risk per 5 dB increase in mean noise exposure (Cantley et al., 2015). Similarly, Shkembi et al. (2022c) observed in the mining sector that each 5 dB increment in mean TWA corresponded to an 8% rise in NFI risk and a 48% increase in FI risk. Our analysis extends these observations to a broader range of occupations and industries, still demonstrating that an increase in mean TWA by 5 dB is associated with a significantly higher risk of NFI (IRR: 1.05, 95% CI: 1.02–1.08) and FI (IRR: 1.06, 95% CI: 1.01–1.12). Moreover, we identified a robust correlation between additional noise metrics and adverse outcomes. In particular, maximum TWA was strongly linked to increased rates of overall and specific NFI types and overall FI rates. Furthermore, TWA exceedance—the proportion of work shifts exceeding the OSHA AL of 85 dBA—was significantly associated with elevated risks of FI and NFI among occupations. These findings suggest that the impact of noise exposure on occupational FIs and NFIs is multifaceted, extending beyond mean noise levels to include maximum exposure levels and the prevalence of exposure over regulatory thresholds. Consequently, our study suggests that a nuanced assessment of noise exposure, considering both average and maximum levels as well as the frequency of hazardous noise exposure, may be warranted and beneficial when considering workplace noise control strategies.

In addition, our research delineated clusters within occupational and industrial categories, defined by distinct noise exposure profiles, which exhibited differential risks for FIs and NFIs. In particular, compared to the low exposure cluster, both the volatile high and constant high exposure clusters had higher FI and NFI risks among occupations. These findings, along with associations between noise metrics and FI rates, confirm the consistently positive relationship between noise exposure and FI risk. While the SD of TWA did not correlate with FI/NFI rates as a single exposure, it did contribute as a characteristic to the significant associations between volatile high exposure cluster and both higher FI and NFI risk. Therefore, we cannot rule out an association between higher exposure variability and higher FI/NFI risk. A detailed evaluation of specific types of NFIs revealed that the volatile high exposure cluster was associated with higher incidence of the NFIs except for amputations, while the constant high exposure cluster is associated with higher rates of factures, cuts, lacerations, punctures, and chemical burns. This suggests that the characteristics of noise exposure—for instance, fluctuating versus stable and sustained noise—may predispose workers to different types of NFIs.

Notably, the differential effects observed in our study between various noise metrics and exposure clusters on injury outcomes underscore the complexity of occupational noise as a risk factor. Different noise metrics reflect distinct dimensions of noise exposure that may influence workers' susceptibility to injuries in varied ways. For instance, mean TWA represents the average noise level, which might contribute to cumulative stress and fatigue, gradually impairing cognitive functions and decision-making over time (Golmohammadi et al., 2021; Tseng and Liu, 2018). On the other hand, maximum TWA better reflects the highest noise levels encountered, which might trigger acute stress responses or sudden distractions, potentially leading to immediate safety hazards (Szalma and Hancock, 2011). The exceedance percentage reflects the frequency of exposure to hazardous noise, with higher frequencies presumably increasing the likelihood of accidents due to repeated high-risk situations (Smith, 2011). The clustering analysis provides further insights into how variability and consistency of noise exposure patterns might differentially affect injury risks. Occupations within the 'volatile high exposure' cluster, characterized by significant fluctuations in noise levels, may induce cognitive overload or mental fatigue, compromising a worker's ability to maintain attention and situational awareness, thereby increasing the potential for errors and accidents. Shkembi et al. (2022b) highlighted that such fluctuations in noise, particularly the difference between peak and mean exposures, are strongly associated with elevated mental workload. This elevated mental workload may reduce workers' cognitive performance and hazard perception, further exacerbating the risk of injury. Similarly, the meta-analysis by Szalma and Hancock (2011) showed that noise characteristics, such as intensity and variability, have differential impacts on cognitive and motor performance, with intermittent and variable noise schedules being particularly disruptive. These findings suggest that the cognitive load imposed by fluctuating noise levels could explain the higher injury risks observed in the volatile high exposure cluster. Conversely, constant high exposure occupations involve sustained exposure to high noise levels, which could lead to chronic stress, habituation to hazardous conditions, and a false sense of security among workers (Swaen et al., 2003). This sustained exposure might dull a worker's alertness over time, making them less responsive to dangers and thus heightening the risk of both nonfatal and fatal injuries.

An intriguing aspect of our findings is the disparity in the significance of associations between occupations and industries. Notably, significant associations were predominantly observed within occupations, with industries showing fewer meaningful associations. As illustrated in Supplementary Figs. S14 and S15, we observed a greater spread in the distribution of noise exposure metrics and outcomes among occupations compared to industries. Further, considering the inclusions/exclusions of occupation-years/industry-years that were displayed in Supplementary Figs. S10–S13, we concluded that occupational categories are potentially more representative, since they are more specific and capture more precisely the variability in noise exposure and FI/NFI rates. Conversely, industries are broader categories that encapsulate many different types of jobs, which lead to more homogenized noise exposure and FI/NFI rates. For instance, within the construction industry, both administrative staff and on-site workers are included, but their risk profiles for noise exposure and injury are vastly different. When analyzing at the industry level, these differences are averaged out, potentially obscuring significant associations.

Our study, while informative, has several limitations. First and foremost, the ecological design hinders causal interpretation due to potential ecological fallacy. As such, the results should be interpreted with caution and not directly applied to individual workers. The significant associations observed nationwide across many occupations and years provide important evidence of the link between workplace noise and injuries, but these findings reflect group-level trends rather than individual-level outcomes. Secondly, data accessibility issues in noise measurements resulted in the omission of certain occupations and industries, as detailed in Supplementary Tables S17 and S18. Specifically, the median FI and NFI rates of the majority of excluded occupations and the NFI rates of the most excluded industries were lower than the median of the included data. Also, many of the excluded occupations were expected *a priori* to have lower level of noise exposure. Therefore, the possible indication of positive associations from the excluded data may reinforce our current estimates if we included these data in future analyses. Among the excluded industries, the oil and gas extraction and transportation industries are not necessarily "quiet" and their median FI rates are higher than the median of the included data, while the information and finance and insurance industries are likely quieter and less dangerous than the median of the included data. As a result, we might have underestimated the associations between noise exposure and FI rates among industries since the excluded data might provide evidence on the positive associations between noise exposure and FI rates. Thirdly, noise exposure could potentially serve as a proxy for other occupational hazards, such as physical workload, vibration, or chemical exposures, which are common in noisy environments. Although we conducted a sensitivity analysis using an expert-driven hazard score to account for these factors, this approach may not fully capture all relevant co-exposures or the complex interactions between different hazards. Therefore, while our findings suggest a strong association between noise exposure and injury risk, we cannot entirely rule out the possibility that other unmeasured hazards are contributing to these associations. Further research with more detailed exposure assessments is needed to disentangle the effects of noise from other occupational risks. Lastly, the study did not include hearing loss prevalence or HPD usage due to the lack of available data. Hearing loss can significantly impair communication and hazard awareness, thereby increasing the risk of accidents and injuries in the workplace (Girard et al., 2015; Morata et al., 2005). Effective HPD use can mitigate these effects (Green et al., 2021), yet inconsistent or improper HPD usage may create a false sense of security and not fully prevent hearing loss or related risks (Neitzel and Seixas, 2005), and overprotection – wherein workers receive much more noise attenuation than their exposure requires – essentially induces a temporary hearing loss among impacted workers. Despite these limitations, the study contributes valuable insights. The extensive dataset covering a large window of time provides temporal depth to the noise-injury correlation analysis. Employing multiple noise metrics allowed for a detailed evaluation of noise exposure risks. Additionally, our use of mixed-effects models to adjust for time and occupation/industry variations strengthened the reliability of our results, ensuring applicability across different work environments. Lastly, the application of a k-means clustering algorithm allowed for novel interpretations of complex data.

The findings of our study suggest multiple directions for future research. Firstly, in addition to significant findings observed in this ecological study, workplace noise has consistently been associated with elevated injury risk among multiple ecological (Shkembi et al., 2022c), cross-sectional (Amjad-Sardrudi et al., 2012; Neitzel et al., 2015), and prospective cohort studies (Cantley et al., 2015). However, no individual-level cohort studies have been conducted nationally across many occupations and industries. In light of this evidence, a comprehensive, nationwide, longitudinal research study may be warranted. Moreover, there is a clear need to broaden noise measurements collection efforts to include a wider range of occupations and industries to improve the representativeness and accuracy of research findings. Finally, data on hearing loss prevalence and the utilization of HPDs are critical. Studying how noise exposure interacts with these factors could provide clarity on the underlying mechanisms of noise-induced injuries and identify targets for interventions, contributing to more effective risk management strategies in the workplace.

5. Conclusions

Our study demonstrated a significant association between occupational noise exposure and the incidence of workplace FIs and NFIs. Our findings reveal that noise exposure is not unidimensional but varies in impact across different noise metrics. Mean TWA, maximum TWA, and TWA exceedance were significantly associated with an increased risk of both workplace FIs and NFIs. Occupations experiencing both volatile high and constant high exposure faced notably higher risks. Our findings, considered in combination with the previous literature, suggest a pressing need for enhanced injury prevention measures and updated noise regulations. We recommend enhancing noise monitoring practices, particularly in occupations and industries at higher-risk due to high variability and peak noise levels. Regulations should be updated to consider not only average noise levels but also the frequency and extent of noise exceedances. Additionally, tailored noise reduction strategies should be implemented in sectors with persistent high exposure, emphasizing both engineering controls and administrative measures.

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CRediT authorship contribution statement

Jie He: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Lauren M. Smith:** Writing – review & editing, Validation, Project administration, Investigation, Conceptualization. **Abas Shkembi:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Richard L. Neitzel:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2024.114468.

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