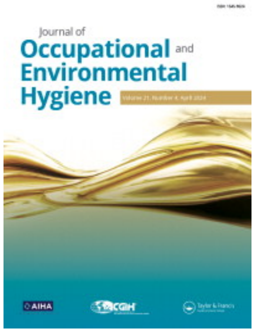

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REPORT

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Respirable dust and crystalline silica concentrations among workers at a brick kiln in Bhaktapur, Nepal

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ABSTRACT

Exposure to respirable dust and crystalline silica (SiO_2) has been linked to chronic obstructive pulmonary disease, silicosis, cancer, heart disease, and other respiratory diseases. Relatively few studies have measured respirable dust and SiO_2 concentrations among workers at brick kilns in low- and middle-income countries. The purpose of this study was to measure personal breathing zone (PBZ) respirable dust and SiO_2 concentrations among workers at one brick kiln in Bhaktapur, Nepal. A cross-sectional study was conducted among 49 workers in five job categories: administration, fire master, green (unfired) brick hand molder, green brick machine molder, and top loader. PBZ air samples were collected from each worker following Methods 0600 (respirable dust) and 7500 (respirable crystalline SiO_2: cristobalite, quartz, tridymite) of the U.S. National Institute for Occupational Safety and Health. Eight-hour time-weighted average (TWA) respirable dust and quartz concentrations were also calculated. SiO_2 percentage was measured in one bulk sample each of wet clay, the release agent used by green brick hand molders, and top coat soil at the brick kiln. The geometric mean (GM) sample and TWA respirable dust concentrations were 0.20 (95% confidence interval [CI]: 0.16, 0.27) and 0.12 (95% CI: 0.09, 0.16) mg/m^3, respectively. GM sample and TWA quartz concentrations were 15.28 (95% CI: 11.11, 21.02) and 8.60 (95% CI: 5.99, 12.34) µg/m^3, respectively. Job category was significantly associated with GM sample and TWA respirable dust and quartz concentrations (all $p < 0.0001$). Top loaders had the highest GM sample and TWA respirable dust concentrations of 1.49 and 0.99 mg/m^3, respectively. Top loaders also had the highest GM sample and TWA quartz concentrations of 173.08 and 114.39 µg/m^3, respectively. Quartz percentages in bulk samples were 16%-27%. Interventions including using wet methods to reduce dust generation, administrative controls, personal protective equipment, and education and training should be implemented to reduce brick kiln worker exposures to respirable dust and SiO_2.

KEYWORDS
Air quality; brick worker; exposure assessment; international occupational health

Introduction

Respirable dust includes airborne particles that can be inhaled through the nose or mouth and subsequently penetrate to the unciliated airways in the pulmonary region of the lungs (Brown et al. 2013; Bustamante-Marin and Ostrowski 2017). By convention, exposure assessments for respirable dust are conducted with size-selective samplers (i.e., cyclones) that capture particles with a 4.0 µm aerodynamic diameter with 50% efficiency (4.0 µm cut-point) (Brown et al. 2013; Occupational Safety and Health Administration 2023a). Acute exposure to respirable dust can lead to airway and eye irritation, throat infections, sneezing, and exacerbations of asthma. Chronic exposure to respirable dust can lead to chronic obstructive pulmonary disease, heart disease, cancer, and pneumoconiosis (Habybabady et al. 2018). To minimize health effects, the U.S. Occupational Safety

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and Health Administration (OSHA) set an eight-hour time-weighted average (TWA) permissible exposure limit (PEL) of 5 mg/m^3 for respirable dust (Occupational Safety and Health Administration 2023b). However, relatively little is known about respirable dust concentrations among brick kiln workers in low- and middle-income countries, including Nepal.

Crystalline silica (SiO_2) is a naturally occurring mineral abundant in the Earth's crust and commonly found in diverse construction materials. Three common types of SiO_2 are cristobalite, quartz, and tridymite. SiO_2 can become aerosolized and inhaled when it is naturally or mechanically crushed, ground, or pulverized. Exposure to respirable crystalline SiO_2 particles has been linked to silicosis, lung cancer, and a spectrum of debilitating respiratory diseases (Steenland and Sanderson 2001). OSHA established a TWA PEL of 50 $\mu m/m^3$ for respirable SiO_2 (Occupational Safety and Health Administration 2022). However, Nepal has not yet adopted an occupational regulatory standard for respirable SiO_2 even though occupational settings such as brick kilns still have potentially high SiO_2 concentrations (Thygerson et al. 2019).

The purpose of this study was to measure PBZ respirable dust and SiO_2 concentrations among workers at one brick kiln in Bhaktapur, Nepal, and determine whether concentrations differed by job category. A limited number of soil samples were also obtained in which to measure SiO_2 percentage. This study aimed to address limitations of previous studies by collecting PBZ samples, using a sampling time longer than three hours and as close as possible to a full shift (usually 8–14 hr per day), using a larger sample size than previous studies of SiO_2 concentrations, and reporting respirable dust and SiO_2 concentrations by job category. This study also included workers from two job categories that had not been included in previous studies. The results will help focus interventions on brick kiln workers in job categories that have the highest respirable dust and SiO_2 concentrations and, therefore, the greatest risk of developing adverse health effects.

Methods

Study design

A cross-sectional, observational study design was used to evaluate respirable dust and SiO_2 exposures among brick workers in Bhaktapur, Nepal. Brickmaking in the Kathmandu Valley occurs from November to March, during the dry season. Data collection took place from March 13–20, 2023. The study sample consisted of 49 participants from a single induced-draught zigzag kiln (IDZK). IDZKs are coal-fed kilns in which a fan is used to pull hot air and flue gases across bricks that are stacked in a manner that moves the air in a zigzag pattern. The zigzag stacking pattern increases heat distribution and the contact time the air has with the bricks, which results in better brick quality and fuel efficiency (MinErgy Nepal 2015; Yadav and Kumar 2017). All participants were adult employees of the brick kiln sampled from five job categories: administration, fire master, green brick hand molder, green brick machine molder, and top loader (Figure 1). All participants were sampled during their regular work shifts during daytime hours. One to four (mean: 2.45; standard deviation: 0.87) air samples were collected for each participant and the median sampling time per worker was 334 (interquartile range: 118) minutes (5.57 h). Steps in the brick manufacturing process included (1) molding green (unfired) bricks from wet clay, (2) sun-drying green bricks, (3) stacking green bricks in the kiln, (4) firing green bricks, (5) removing red (fired) bricks from the kiln, and (6) sorting and stacking red bricks.

Workers in all job categories performed tasks that had varying degrees of dust exposure. The administration job category consisted of office workers and supervisory personnel. Administration workers differed from participants in other job categories because they tended to move around the brick kiln property, spending more time inside office spaces, and less time near brick manufacturing tasks where they had limited, intermittent dust exposure. They also tended to live away from the brick kiln in improved housing compared to those in other job categories. Fire masters included workers with the primary job task of adding coal through chutes on the top of the kiln. Their primary dust exposures were from dry coal being added to the kiln, and from fugitive dust generated by top loaders. Green brick hand and machine molders included participants who made green bricks using hand molds or who worked in the machine molding area making or moving the bricks, respectively. Green brick hand molders worked with wet clay and the dry release agent. There was visible dust around workers when they applied the release agent to the brick mold, but no visible dust when they worked with wet clay. Top loaders included participants who removed the layer of soil from the top of the brick kiln after the bricks were fired. There was significant suspended dust around top loaders while they removed soil from the kiln. Fire masters and top loaders worked outdoors on top of the kiln, but underneath a metal awning with no side walls (Figure 1, panels a and d). Green brick hand molders worked exclusively outdoors (Figure 1, panel b). Green brick machine molders worked indoors (Figure 1, panel c) and under canopies made with bamboo frames covered with plastic sheeting (not shown). Administration personnel moved between indoor office/building spaces and outdoor brick manufacturing operations while working.

Ethical approval for this study was obtained from the Institutional Review Boards (IRB) at Bringham

Figure 1. Photographs of workers in different job categories at a brick kiln in Bhaktapur, Nepal, March 2023: (a) fire master, (b) green brick hand molder, (c) green brick machine molder, and (d) top loader. Photographs by Jaren Wilkey, University Communications, Bringham Young University, Provo, UT, USA (panels a, b, d), and Clifton B. Farnsworth, Department of Civil and Construction Engineering, Bringham Young University, Provo, UT, USA (panel c).

Figure 1. Continued.

Young University (BYU), the Nepal Health Research Council, and the University of Utah. Written informed consent was obtained from each participant before data collection.

Measurement of personal breathing zone respirable dust and crystalline SiO_2

PBZ respirable dust and SiO_2 were sampled using U.S. National Institute for Occupational Safety and Health (NIOSH) Methods 0600 and 7500, respectively (National Institute for Occupational Safety and Health 2003a, 2003b). Both respirable dust and SiO_2 samples were collected using SKC AirLite pumps and size-selective samplers (SKC Incorporated, Fullerton, CA, USA). The sampler consisted of a 37 mm aluminum cyclone attached to a three-piece, 37 mm cassette holding 5.0 µm PVC matched weight filters (ALS Environmental, Salt Lake City, UT, USA). Deionized water was used to wet the O-ring on the cyclone before attaching it to the cassette. The cyclone/cassette assembly was attached to participants in the PBZ using filter cassette holders (SKC Incorporated, Fullerton, CA, USA). For this study, the PBZ was considered to include air within approximately 23 cm (~ nine inches) of workers' mouths/noses. The cyclone/cassette assembly was attached to the pumps with Tygon tubing. Brick worker clothing did not always provide a reliable point of connection for the pumps, so pumps were attached at workers' waists on a sampling vest.

Pumps were pre-calibrated using one of three Mesa Labs Defender 510 Mid-flow dry calibrators (Mesa Laboratories, Inc., Lakewood, CO, USA). To pre-calibrate the pumps, the sampling train was set up as it would be used on a participant but the cassette/filter was replaced with a calibration blank from the same lot used for our samples. Each pump was calibrated to 2.5 L/m ± 1.0%. The sampling train was attached to the participant, the filter number and participant ID number were confirmed, the pump was started, and the start time was recorded. With help from an interpreter, research personnel ensured participants were comfortable and explained to workers to not tip the cassette holder upside down to prevent particles in the grit pot from falling onto the filter. Participants then returned to their work areas. Cassettes/filters were changed approximately every two hours during sampling to prevent overloading. After sampling, pumps were post-calibrated using the same Mesa Labs Mid-flow dry calibrator that was used for pre-calibration.

All cassettes/filters and 10 field blanks were hand-delivered to an AIHA-accredited laboratory in Salt Lake City, UT, USA, by research personnel within six weeks of returning from Nepal. Samples were analyzed for respirable dust using NIOSH Method 0600 (National Institute for Occupational Safety and Health 2003a) modified by the laboratory to include procedures for matched-weight PVC filters. Specifically, matched-weight filters were conditioned in the weighing room for a minimum of 30 min before weighing. The laboratory also conducted duplicate weights once every five samples as an added quality control measure. Duplicate weights were required to be within 0.01 mg of each other. Samples were analyzed for three types of respirable crystalline SiO_2 (cristobalite, quartz, tridymite) using NIOSH Method 7500, which uses X-ray Diffraction (XRD) (National Institute for Occupational Safety and Health 2003b).

Measurement of crystalline SiO_2 in soil

One bulk sample each of wet clay, the release agent used by green brick hand molders, and top coat soil (the soil layer placed over bricks during firing) were collected in plastic resealable bags. Wet clay was made in bulk at the brick kiln and delivered in smaller batches to green brick hand molders' worksites. The bulk sample was collected from a clay batch at one green brick hand molder worksite. The release agent was a dry, powdery soil dug by brick kiln employees from a hillside near the factory. Nothing was added to the release agent before use. The release agent was used by green brick hand molders to coat the inside of the brick mold before adding wet clay. This allowed the newly formed brick to be removed from the mold without it being damaged. The bulk sample was collected at the worksite of a green brick hand molder. Samples were delivered to an AIHA-accredited laboratory in Salt Lake City, UT, USA, for analysis within six weeks of returning from Nepal. Bulk samples were analyzed for three types of crystalline SiO_2 (cristobalite, quartz, tridymite) following NIOSH Method 7500, which uses XRD (National Institute for Occupational Safety and Health 2003b).

Statistical analyses

SAS version 9.4 (SAS Institute Inc., Cary, NC, USA) was used for data management and statistical analyses. To calculate air pollutant concentrations, all samples needed to have air pollutant masses measured above lower detection limits (LDL) so they could be summed to obtain the total air pollutant masses for each worker. However, 10 (8%), 120 (100%), 82 (68%), and 120 (100%) of the 120 total samples collected had respirable dust, cristobalite, quartz, and tridymite masses below LDLs, respectively. Therefore, cristobalite and tridymite were not included in further analyses. Multiple imputation was used to impute respirable dust and quartz masses between zero and the LDL for samples that had respirable dust and quartz masses below LDLs (Lubin et al. 2004). Multiple imputation provides unbiased estimates and nominal confidence interval coverage, whereas more common methods of dealing with measurements below detection limits, such as dividing LDLs by two or $\sqrt{2}$, are widely known to be biased and provide less than nominal confidence interval coverage when the percentage of measurements below detection limits is greater than 5–10% (Lubin et al. 2004; Helsel 2010; Huynh et al. 2014). The default settings of PROC MI, which assumes a multivariate normal distribution, and the seed 752442 were used to impute 100 datasets. The imputation model included the variables respirable dust mass, quartz mass, average sampling pump flow rate, sampling time, and job category.

Although PROC MI has options that allow the restriction of imputed values within a specified range (e.g., between zero and the LDL), PROC MI kept generating errors when these options were used. Therefore, following the advice in a SAS usage note (SAS Institute Inc. 2006), the datasets were imputed without using those options, and then the imputed masses were constrained to be between zero and the LDL via a six-step process (Supplemental Material, p. 2; an example is included in the Supplemental Material). The sample masses that measured above the LDL and the imputed sample masses that were constrained to be between zero and the LDL were then summed to obtain the total respirable dust and quartz masses for each worker. The total respirable dust and quartz masses, the average sampling pump flow rates, the sampling times, and established formulas (Johnston et al. 2022) were used to calculate respirable dust and quartz concentrations for each worker. TWA respirable dust and quartz concentrations were also calculated for each worker using established formulas (Watchman 1997).

Frequencies and percentages were calculated of workers who had respirable dust, cristobalite, quartz, and tridymite masses above LDLs overall and/or for each job category (i.e., before using multiple imputations). The distributions of sample and TWA respirable dust and quartz concentrations were right-skewed. Therefore, separate intercept-only linear regression models of the multiply imputed (MI) natural logarithm transformed sample and TWA respirable dust and quartz concentrations and PROC MIANALYZE were used to calculate overall MI geometric means (GM) and 95% confidence intervals (CI) for sample and TWA respirable dust and quartz concentrations. Separate simple (i.e., unadjusted) linear regression models of the MI natural logarithm transformed sample and TWA respirable dust and quartz concentrations and PROC MIANALYZE were used to calculate MI GM, 95% CI, and p-values for associations between job category and sample and TWA respirable dust and quartz concentrations. Using the Tukey-Kramer method to adjust for multiple comparisons and PROC MIANALYZE, pairwise comparisons were conducted among job categories if MI associations between job category and sample or TWA respirable dust or quartz concentrations were statistically significant at $\alpha = 0.05$.

A sensitivity analysis was conducted in which two things were done. First, one participant was excluded from the analysis because that participant did not work the day air samples were collected for that participant (the measured respirable dust and quartz masses were likely too low). Second, the respirable dust and quartz masses for two samples (one sample each for two separate participants) were set to the LDLs because the cassettes tipped over as they were being taken off, so the larger particles in the grit pot may have fallen onto the cassettes (the cassettes may have been contaminated and the measured respirable dust and quartz masses may have been too high).

Results

Of the 49 participants, 14%, 16%, 33%, 22%, and 14% were in the job categories administration, fire master, green brick hand molder, green brick machine molder, and top loader, respectively (Table 1). All workers had respirable dust masses above the LDL for at least one air sample. The workers' overall MI GM sample and TWA respirable dust concentrations were 0.20 (95% CI: 0.16, 0.27) mg/m^3 and 0.12 (95% CI: 0.09, 0.16) mg/m^3, respectively. Job category was significantly associated with workers' MI GM sample and TWA respirable dust concentrations (both MI $p < 0.0001$). After adjusting for multiple comparisons using the Tukey-Kramer method, pairwise comparisons found the MI GM sample respirable dust concentration among top loaders (GM: 1.49, 95% CI: 1.08, 2.07 mg/m^3) was significantly different from those of workers in the other four job categories (all MI $p < 0.0001$). The same pattern was observed for MI GM TWA respirable dust concentrations. In addition, pairwise comparisons found a significant difference (MI $p = 0.05$) between the MI GM TWA respirable dust concentrations of green brick hand molders (GM: 0.07, 95% CI: 0.05, 0.09 mg/m^3) and green brick machine molders (GM: 0.14, 95% CI: 0.09, 0.18 mg/m^3). The results of the sensitivity analysis were similar (not shown).

Forty-five percent of workers had quartz masses above the LDL for at least one air sample (Table 2). The overall MI GM sample and TWA quartz concentrations among workers were 15.28 (95% CI: 11.11, 21.02) $\mu g/m^3$ and 8.60 (95% CI: 5.99, 12.34) $\mu g/m^3$, respectively. Of the workers who had quartz masses above the LDL, 14%, 0%, 18%, 36%, and 32% were in the job categories administration, fire master, green brick hand molder, green brick machine molder, and top loader, respectively. There were significant associations between job category and workers' MI GM sample and TWA quartz concentrations (both MI $p < 0.0001$). After adjusting for multiple comparisons

Table 1. Associations between job category and personal breathing zone respirable dust concentrations[a] among workers[b] at a brick kiln in Bhaktapur, Nepal, March 2023.

		Respirable dust (mg/m³)					
		MI Sample			MI TWA		
Characteristic	Above LDL[c], n (%)	GM	95% CI	*p*-value	GM	95% CI	*p*-value
Overall	49 (100)	0.20[d]	0.16, 0.27[d]		0.12[d]	0.09, 0.16[d]	
Job category							
Administration	7 (14)	0.11[e]	0.08, 0.15[e]		0.07[e]	0.04, 0.10[e]	
Fire master	8 (16)	0.14[e]	0.10, 0.19[e]		0.06[e]	0.04, 0.09[e]	
Green brick hand molder	16 (33)	0.15[e]	0.12, 0.19[e]		0.07[e]	0.05, 0.09[e]	
Green brick machine molder	11 (22)	0.18[e]	0.14, 0.24[e]		0.14[e]	0.09, 0.18[e]	
Top loader	7 (14)	1.49[e]	1.08, 2.07[e]	<0.0001[e,f]	0.99[e]	0.65, 1.50[e]	<0.0001[e,g]

Abbreviations: CI, confidence interval; GM, geometric mean; LDL, lower detection limit; MI, multiply imputed; OSHA, U.S. Occupational Safety and Health Administration; PEL, permissible exposure limit; TWA, eight-hour time-weighted average.
[a]The OSHA PEL for respirable dust is a TWA of 5 mg/m³ (Occupational Safety and Health Administration 2023b).
[b]One sample was missing because one of the 50 workers enrolled in the study declined to participate in the personal breathing zone air sampling.
[c]The LDL mass for respirable dust was 0.02 mg.
[d]Estimated using multiple imputation and intercept only linear regression models of the natural logarithm transformed values.
[e]Estimated using multiple imputation and simple (i.e., unadjusted) linear regression models of the natural logarithm transformed values.
[f]After adjusting for multiple comparisons using the Tukey-Kramer method, tests of pairwise differences among job categories had the following *p*-values: Administration *vs.* Fire master: 0.82, Administration *vs.* Green brick hand molder: 0.50, Administration *vs.* Green brick machine molder: 0.13, Administration *vs.* Top loader: <0.0001, Fire master *vs.* Green brick hand molder: 0.99, Fire master *vs.* Green brick machine molder: 0.68, Fire master *vs.* Top loader: <0.0001, Green brick hand molder *vs.* Green brick machine molder: 0.79, Green brick hand molder *vs.* Top loader: <0.0001, Green brick machine molder *vs.* Top loader: <0.0001.
[g]After adjusting for multiple comparisons using the Tukey-Kramer method, tests of pairwise differences among job categories had the following *p*-values: Administration *vs.* Fire master: >0.99, Administration *vs.* Green brick hand molder: >0.99, Administration *vs.* Green brick machine molder: 0.13, Administration *vs.* Top loader: <0.0001, Fire master *vs.* Green brick hand molder: >0.99, Fire master *vs.* Green brick machine molder: 0.07, Fire master *vs.* Top loader: <0.0001, Green brick hand molder *vs.* Green brick machine molder: 0.05, Green brick hand molder *vs.* Top loader: <0.0001, Green brick machine molder *vs.* Top loader: <0.0001.

Table 2. Associations between job category and personal breathing zone respirable crystalline SiO_2 concentrations[a] among workers[b] at a brick kiln in Bhaktapur, Nepal, March 2023.

			MI Sample			MI TWA		
SiO_2 Type/Characteristic	Below LDL[c], n (%)	Above LDL[c], n (%)	GM	95% CI	*p*-value	GM	95% CI	*p*-value
Cristobalite, μg/m³								
Overall	49 (100)	0 (0)						
Quartz, μg/m³								
Overall	27 (55)	22 (45)	15.28[d]	11.11, 21.02[d]		8.60[d]	5.99, 12.34[d]	
Job category								
Administration	4 (15)	3 (14)	8.81[e]	5.99, 12.97[e]		5.49[e]	3.36, 8.98[e]	
Fire master	8 (30)	0 (0)	7.82[e]	5.43, 11.25[e]		3.62[e]	2.28, 5.73[e]	
Green brick hand molder	12 (44)	4 (18)	10.06[e]	7.72, 13.11[e]		4.69[e]	3.37, 6.54[e]	
Green brick machine molder	3 (11)	8 (36)	13.84[e]	10.19, 18.81[e]		9.97[e]	6.75, 14.73[e]	
Top loader	0 (0)	7 (32)	173.08[e]	117.96, 253.95[e]	<0.0001[e,f]	114.39[e]	70.19, 186.43[e]	<0.0001[e,g]
Tridymite, μg/m³								
Overall	49 (100)	0 (0)						

Abbreviations: CI, confidence interval; GM, geometric mean; LDL, lower detection limit; MI, multiply imputed; OSHA, U.S. Occupational Safety and Health Administration; PEL, permissible exposure limit; SiO_2, silica; TWA, eight-hour time-weighted average.
[a]The OSHA PEL for respirable crystalline SiO_2 is a TWA of 50 μg/m³ (Occupational Safety and Health Administration 2022).
[b]One sample was missing because one of the 50 workers enrolled in the study declined to participate in the personal breathing zone air sampling.
[c]The LDL masses for respirable crystalline cristobalite, quartz, and tridymite were 5, 5, and 20 μg, respectively.
[d]Estimated using multiple imputation and intercept only linear regression models of the natural logarithm transformed values.
[e]Estimated using multiple imputation and simple (i.e., unadjusted) linear regression models of the natural logarithm transformed values.
[f]After adjusting for multiple comparisons using the Tukey-Kramer method, tests of pairwise differences among job categories had the following *p*-values: Administration *vs.* Fire master: 0.99, Administration *vs.* Green brick hand molder: 0.97, Administration *vs.* Green brick machine molder: 0.39, Administration *vs.* Top loader: <0.0001, Fire master *vs.* Green brick hand molder: 0.78, Fire master *vs.* Green brick machine molder: 0.15, Fire master *vs.* Top loader: <0.0001, Green brick hand molder *vs.* Green brick machine molder: 0.52, Green brick hand molder *vs.* Top loader: <0.0001, Green brick machine molder *vs.* Top loader: <0.0001.
[g]After adjusting for multiple comparisons using the Tukey-Kramer method, tests of pairwise differences among job categories had the following *p*-values: Administration *vs.* Fire master: 0.73, Administration *vs.* Green brick hand molder: 0.98, Administration *vs.* Green brick machine molder: 0.35, Administration *vs.* Top loader: <0.0001, Fire master *vs.* Green brick hand molder: 0.88, Fire master *vs.* Green brick machine molder: 0.02, Fire master *vs.* Top loader: <0.0001, Green brick hand molder *vs.* Green brick machine molder: 0.04, Green brick hand molder *vs.* Top loader: <0.0001, Green brick machine molder *vs.* Top loader: <0.0001.

using the Tukey-Kramer method, pairwise comparisons found the MI GM sample quartz concentration among top loaders (GM: 173.08, 95% CI: 117.96, 253.95 μg/m³) was significantly different from those of workers in the other four job categories (all MI $p < 0.0001$). The same pattern was observed for MI GM TWA quartz concentrations. In addition, pairwise comparisons found significant differences (MI

$p = 0.02$) between the MI GM TWA quartz concentrations of fire masters (GM: 3.62, 95% CI: 2.28, 5.73 μg/m^3) and green brick machine molders (GM: 9.97, 95% CI: 6.75, 14.73 μg/m^3) and between green brick hand molders (GM: 4.69, 95% CI: 3.37, 6.54 μg/m^3) and green brick machine molders (MI $p = 0.04$). The results of the sensitivity analysis were similar (not shown).

Cristobalite and tridymite were not found above the LDL in any of the bulk samples. However, quartz made up 24%, 27%, and 16% of the clay, release agent, and top coat soil samples, respectively.

Discussion

Clay bricks are a low-cost building material, and consequently, brick manufacturing is a major industry globally, particularly in low- and middle-income countries. In South Asia, for example, Bangladesh, India, Pakistan, and Nepal combined have more than 165,000 brick kilns and an estimated 18 million workers engaged in brick production (Kamal et al. 2014; Eil et al. 2020). Globally, there is also a growing body of literature suggesting clay brick manufacturing is associated with serious respiratory problems among brick workers. Separate studies of brick workers in Punjab and West Bengal, India, reported significantly decreased lung function among brick workers compared to controls, measured as forced expiratory volume in 1 s, forced vital capacity, and peak expiratory flow rate (Das 2014; Tandon et al. 2017). Brick workers in Mexico were likewise found to have decreased lung function which was associated with length of employment in the brick industry (Berumen-Rodríguez et al. 2021). Brick workers in Pakistan and Nepal self-reported significantly higher respiratory symptoms consistent with pneumoconiosis compared to controls (Shaikh et al. 2012; Sanjel et al. 2017). Exposure assessment studies, such as this study, are necessary to identify jobs and job tasks that are associated with hazardous exposures. This information can be used to help prioritize control strategies to decrease dust and SiO_2 exposures and improve lung health. To this end, this study found significant associations between job category and PBZ sample and TWA concentrations of respirable dust and quartz among brick kiln workers in Bhaktapur, Nepal. Top loaders had the highest sample and TWA concentrations of respirable dust and quartz by substantial margins. Top loaders had visibly high dust exposures while removing the dry, insulating layer of soil from off the top layer of bricks after firing. Quartz was also found in bulk samples.

There are few previous studies of respirable dust concentrations among brick kiln workers in low- and middle-income countries. A study conducted at three brick kilns in Cape Town, South Africa, collected 268 full-shift (usually eight hours), PBZ samples and found workers had a mean respirable dust concentration of 2.22 mg/m^3 (Myers et al. 1989). Another study conducted at one brick kiln in Iran collected PBZ samples from 90 workers for a mean sampling time of 2.00 h and reported workers had a mean respirable dust concentration of 2.8 mg/m^3 (Mokarami et al. 2020). A third study conducted at 16 brick kilns in Bhaktapur, Lalitpur, and Kathmandu, Nepal, collected PBZ samples from 72 workers for a mean sampling time of 2.67 h and found a mean TWA respirable dust concentration of 2.588 mg/m^3 (Sanjel et al. 2017). In this study, the GM sample and TWA respirable dust concentrations were 0.20 mg/m^3 and 0.12 mg/m^3, respectively. All of these mean and GM respirable dust concentrations are less than the current OSHA PEL of 5 mg/m^3 for TWA PBZ respirable dust concentration (Occupational Safety and Health Administration 2023b).

The reasons for the much lower respirable dust concentrations found in this study compared to other studies are not obvious. However, possible explanations might include differences between studies in sample sizes, job categories and numbers of workers from each job category that were sampled, locations and administration of brick kilns, statistical analysis methods, and sampling time. Regarding sampling time, this study used a shorter sampling time per sample because of concerns about possible sample overloading based on a previous study conducted among brick kiln workers in Nepal that reported high concentrations of quartz (Sanjel et al. 2018). In fact, the mean sampling time for the 120 air samples collected in this study was 2.00 h (standard deviation: 0.43 h), which may have resulted in underestimates of respirable dust concentrations.

Job category may be associated with respirable dust concentrations at brick kilns. The aforementioned study by Sanjel et al. (Sanjel et al. 2017) found a significant ($p < 0.001$) association between job category and mean TWA respirable dust concentrations. Red brick loading had the highest mean TWA respirable dust concentration (5.888 mg/m^3) followed by coal preparation (2.454 mg/m^3), green brick stacking (1.877 mg/m^3), fireman (fire master; 1.133 mg/m^3), and green brick molding (0.722 mg/m^3). In this study, significant associations were found between job category and GM sample and TWA respirable dust concentrations (both $p < 0.0001$). Top loaders had significantly higher GM sample and TWA respirable dust concentrations (1.49 mg/m^3 and 0.99 mg/m^3, respectively) than administration workers, fire masters, green brick hand molders, and green brick machine molders (all $p < 0.0001$). These results suggest jobs that involve working with red bricks, such as red brick loading and top loading, are much dustier than jobs that involve working with green bricks, such as green brick stacking, green brick hand molding, and green brick machine molding. As explained by other authors (Sanjel et al. 2018, Sanjel et al. 2017), red bricks and the top coat of soil that covers them are dry because of the firing process, which leads to more suspension of dust particles in the air, whereas green bricks are wetter because they have not yet been fired, which leads to less suspension of dust particles in the air.

Few previous studies have measured quartz concentrations among brick kiln workers or at brick kilns in low- and middle-income countries. A study conducted at two brick manufacturing sites in Mazandaran, Iran, collected full-shift (not more than six hours), PBZ samples from 12 workers and found a mean quartz concentration of 194 μg/m^3 (Rokni et al. 2016). Another study conducted at four brick kilns in Bhaktapur, Nepal, collected one stationary sample each from inside and outside 16 homes for a mean sampling time of 6.67 h and found a GM quartz concentration of 6.22 μg/m^3 (Beard et al. 2022). A third study conducted at 16 brick kilns in Bhaktapur, Lalitpur, and Kathmandu, Nepal, collected PBZ samples from 46 workers for a mean sampling time of 2.83 hr but did not report an overall mean or GM quartz concentration (Sanjel et al. 2018). However, they reported GM quartz concentrations for workers in five job categories that ranged between 71 μg/m^3 and 331 μg/m^3. In this study, the GM sample and TWA quartz concentrations were 15.28 μg/m^3 and 8.60 μg/m^3, respectively. Two of these studies reported a mean or GM quartz concentration that was greater than the current OSHA PEL of 50 μg/m^3 for TWA PBZ quartz concentration (Occupational Safety and Health Administration 2022). Possible explanations for the much lower quartz concentrations found in this study compared to these two other studies could include many of the same possible explanations listed for the much lower respirable dust concentrations found in this study compared to other studies.

Job category may also be associated with quartz concentrations at brick kilns. The aforementioned study by Sanjel et al. (2018) found a significant ($p < 0.0001$) association between job category and GM TWA quartz concentrations. Red brick loading/carrying had the highest GM TWA quartz concentration (331 μg/m^3) followed by green brick stacking/carrying (223 μg/m^3), fireman (fire master; 102 μg/m^3), coal crushing/carrying preparation (92 μg/m^3), and green brick molding (71 μg/m^3). In this study, significant associations were found between job category and GM sample and TWA quartz concentrations (both $p < 0.0001$). Top loaders had significantly higher GM sample and TWA quartz concentrations (173.08 μg/m^3 and 114.39 μg/m^3, respectively) than administration workers, fire masters, green brick hand molders, and green brick machine molders (all $p < 0.0001$). The same explanation given previously regarding why jobs that involve working with red bricks have higher respirable dust concentrations than jobs that involve working with green bricks also applies to quartz concentrations.

One previous study, conducted at four brick kilns in Lucknow, India, collected 11 samples from the soil the brick kilns used to make bricks and found a mean SiO_2 percentage of 24.09% (Pangtey et al. 2004). In this study, quartz percentages in bulk samples were similar (16%-27%).

The results of this study suggest that exposure controls should be implemented to reduce PBZ respirable dust and crystalline SiO_2 concentrations among brick kiln workers, especially top loaders. Top loaders are exposed to high levels of quartz while removing the layer of insulating soil from the kiln after the bricks are fired. One potential engineering solution is to find a suitable alternative to soil as the insulating layer. Light-weight, low-density, reusable insulating bricks or ceramic insulation that can be modularized for large brick kilns and moved by hand may provide a cost-effective solution (Etuoku 2013). Heat loss through poor insulation is one of the primary inefficiencies in brick production (Bashir et al. 2023). The use of insulating bricks, if feasible, would serve the dual purpose of reducing worker dust exposures while increasing kiln energy efficiency. Using wet methods, such as spraying or misting the top coat of dirt on top of the brick kiln before it is removed by top loaders, has been shown to effectively reduce dust concentrations in other workplaces and should be used at brick kilns in Nepal (Anlimah et al. 2023). Administrative controls could include not allowing other workers near top loaders when they are removing the insulating soil from the top of the kiln. Filtering facepiece respirators that meet recognized international standards such as NIOSH N-95, European FFP2, or Korea 1st Class should be required for top loaders, and provided for voluntary use by other brick workers. In addition, the provision of respiratory protection would require annual medical evaluations and fit testing of respirators for each worker. Finally, education and training should be provided regarding the health hazards of exposure to respirable dust and SiO_2, proper implementation of wet methods, enforcement of administrative controls, and proper use of personal protective equipment.

One strength of this study was the PBZ was sampled, whereas a previous study (Beard et al. 2022) sampled inside and outside brick kiln workers' homes using stationary air samples. Air and soil samples were also collected using NIOSH's reference methods 0600 (respirable dust) and 7500 (respirable crystalline SiO_2) (National Institute for Occupational Safety and Health 2003a, 2003b). Respirable dust and SiO_2 were measured in air samples collected from brick kiln workers in Nepal, which had been done only once before (Sanjel et al. 2017, 2018). This study had the largest sample size of any study of PBZ SiO_2 concentrations among brick kiln workers to date and the second-longest sampling time for PBZ respirable dust concentrations. Air samples were collected and results were presented for workers in job categories that had never been sampled before (administration, top loaders). Finally, multiple imputation, a statistical method that has been shown to produce unbiased estimates and nominal confidence interval coverage (Lubin et al. 2004), was used to impute values below the LDL.

Limitations

One limitation of this study is it was conducted at one kiln in Bhaktapur, Nepal, so results may not generalize to other kilns in the Kathmandu Valley or elsewhere. In addition, a cross-sectional design was used, so results may not generalize to longer periods including the entire brick-making season. This study had the smallest sample size of any study of PBZ respirable dust concentrations among brick kiln workers to date and the second shortest sampling time for PBZ SiO_2 concentrations. Cassettes were changed after a mean sampling time of two hours, but this may have resulted in the high percentage (68%) of samples that measured below the LDL for quartz and, consequently, underestimated quartz concentrations.

Conclusions

In conclusion, GM PBZ respirable dust and quartz concentrations among workers at the brick kiln studied in Bhaktapur, Nepal, were generally less than the current OSHA PELs. However, top loaders had a GM TWA quartz concentration that was more than double the current OSHA PEL. Top loaders also had the highest GM sample and TWA respirable dust and quartz concentrations of any job category for which air samples were collected. Quartz was found in samples of the clay and release agent used to make bricks and the top coat of dirt on top of the brick kiln. Considering that no previous study included top loaders, additional studies should be conducted on PBZ respirable dust and crystalline SiO_2 concentrations among workers, including top loaders, at brick kilns in Nepal and elsewhere. Interventions such as using wet methods to reduce dust generation, administrative controls, personal protective equipment including respiratory protection, and education and training should be implemented to reduce brick kiln worker exposures to respirable dust and crystalline SiO_2. Future studies should address limitations of this study by collecting PBZ air samples from workers at multiple brick kilns, collecting PBZ air samples from workers more than one time throughout the brick-making season, using a larger sample size, sampling for entire work shifts, and changing cassettes after a longer sampling time.

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The authors report there are no competing interests to declare.

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Data availability

The data that support the findings of this study are available from the corresponding author, JDB, upon reasonable request.

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