The University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Respirable Dust in Ceramic Industries (Iran) and its Health Risk Assessment using Deterministic and Probabilistic Approaches

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Article Info

Article type:
Research Article

Article history:
Received: 3 May 2024
Revised: 12 July 2024
Accepted: 20 August 2024

Keywords:
Dust
Similar exposure groups (SEGs)
Latin hypercube sampling (LHs)
Sensitivity analysis
Hazard quotient (HQ)

ABSTRACT

This study used both deterministic and probabilistic methods to evaluate the risks associated with non-cancer health outcomes for workers in the ceramic industry. In this study, the Similar Exposure Groups (SEGs) method was used to determine the sampling volume. The NIOSH 0600 technique was followed in the collection of breathing zone air samples. Next, the Latin hypercube simulation and the EPA-developed inhalation risk assessment model were used to evaluate the health risks associated with respirable dust. To ascertain how input parameters contributed to the health risks, a sensitivity analysis was also performed. The average exposure to respirable dust in occupational groups ranged from 0.28 to 20.13 mg/m^3. The average respirable dust in all occupational groups, except furnace, glazing line, and packaging, was higher than the values presented according to the ACGIH standard (3 mg/m^3). It was anticipated that the HQ values acquired for all occupational groups using the deterministic approach would be less than 1. However, the probabilistic approach's results indicated that the value of HQ is higher than permissible values in some occupational groups. The findings of the sensitivity analysis showed that the concentration of respirable dust was the most sensitive factor contributing to non-carcinogenic (67.08%) risks. These results can help managers better understand the risks of respirable dust that workers in the ceramic industry confront and how engineering controls and respirators protect workers' health.

Cite this article: Shojaee Barjoee, S., & Rodionov Alekseevich, V. (2024). Respirable Dust in Ceramic Industries (Iran) and its Health Risk Assessment using Deterministic and Probabilistic Approaches. *Pollution*, 10 (4), 1206-1226.
https://doi.org/10.22059/poll.2024.376043.2360

 Publisher: The University of Tehran Press.
DOI: https://doi.org/10.22059/poll.2024.376043.2360

INTRODUCTION

Anything that has the potential to endanger or damage people, property, or equipment is considered a workplace hazard (Kabanov *et al.*, 2023; Rudakov *et al.*, 2021). According to data from the United Nations Development Programme (UNDP), there are about 110 million insecure workers in Latin America (Saldaña-Villanueva *et al.*, 2023). Workers in industrial environments may be subjected to a variety of dangerous chemical elements (Čargonja *et al.*, 2023). Among these dangerous chemical components is dust (Smirnyakov *et al.*, 2022). Particles with an aerodynamic diameter of less than 75 µm that are suspended in the atmosphere until they come to rest due to their own weight are referred to as dust (Korshunov *et al.*, 2023; Wippich *et al.*, 2020). Dust particles are classified as inhalable, thoracic, or respirable dust fractions based on their aerodynamic diameter, which allows them to enter different parts of the respiratory system (Wippich *et al.*, 2020).

Particles with a diameter of up to 100 µm comprise the portion of dust that can be inhaled (Wippich *et al.*, 2020). Any portion of particles that can pass through the terminal bronchioles

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and enter the gas-exchange area of the lungs is referred to as respirable dust, which is a subset of inhalable dust (Ambastha & Haritash, 2021). Exposure to dust is common in many industries, including foundries, stone and woodworking, mining, the chemical and food industries, and woodworking (Saleiro *et al*., 2019; Wippich *et al*., 2020). Dust at these workplaces poses a health risk to employees even at low concentrations because it is strongly linked to respiratory problems (Che Huei *et al*., 2020). According to the Occupational Health and Safety Institute (NIOSH), over two million workers in the US are exposed to hazardous dust, including asbestos and crystalline silicate (Kalantary *et al*., 2019).

Ceramic output has increased dramatically, almost doubling globally in recent years. The manufacturing of metals, rubber, and plastic products; mining and quarrying, particularly for copper and aluminum; and ceramics are Iran's top four industrial sectors (Jamali *et al*., 2023). Iran's ceramic production capacity has significantly increased due to its unique reserves in numerous mines, extremely low energy prices relative to other nations, and the backing of local industrialists. These factors have also created the foundation for Iran to export its ceramic products to numerous countries worldwide (Carey & Carey, 1975). Iran is the 5th-largest ceramic producer in the world, making this an important industry (https://www.tehrantimes.com/news/495056/). In 2016, the export of about 400 million dollars of ceramic to 69 prestigious countries around the world made Iran the largest ceramic production hub in the region. Along with this success, many people were employed in this industry. The ceramics industry often generates large economic gains, despite the drawbacks associated with high energy consumption and pollutant emissions. Workers in the ceramic industry may also experience serious health risks as a result of fugitive dust emissions that are not under control.

Because raw materials are usually found in particle form throughout the ceramic production process, the handling and processing of these materials is the main cause of excessive dust in the ceramic industry. Research has verified that the detrimental impact of dust on one's health is contingent upon the dust's size, concentration, and hazardous constituents (Chamdimba *et al*., 2023). The smaller particle size and larger specific surface area, which are mostly created during mechanical operations including stockpiling, initial crushing and grinding, abrasion, and raw material processing, are the sole differences with respect to parent materials (Kung *et al*., 2023; Saramak, 2021). The parent materials utilized in the business have a significant impact on the physico-chemical characteristics of dust (Paluchamy & Mishra, 2022). Different components, such as minerals, metallic particles, and organic particles, can make up dust, and these materials can vary widely in size, shape, and density (Wippich *et al*., 2020). Dust from clay materials—such as grog, vermiculite, perlite, sand, and glaze—contains significant levels of free silica, which can cause lung tissue damage and lead to respiratory conditions like pneumonia, emphysema, dry cough, asthma, and tuberculosis. The pulverization of clay and sand, as well as the polishing of green ceramic ware, also produce hazardous silica dust (Kar *et al*., 2023).

Because they inhale fine silica particles when mixing clay and preparing glazes, workers in hygienic ceramic companies are susceptible to silicosis, the most common occupational disease in the world. The respiratory illnesses kaolinosis, aluminosis, and talcosis are caused by long-term inhalation and exposure to kaolin, alumina, and talc dust, respectively (Huang *et al*., 1993). Fibrous asbestos is a common contaminant of clay slip that is extremely hazardous when consumed or inhaled. Mesothelioma, intestine cancer, stomach cancer, lung cancer, and asbestosis are among the health risks associated with asbestos inhalation. Ceramic products are made from materials that are poisonous due to the presence of lead, arsenic, antimony, beryllium, cadmium, chromium, selenium, vanadium, manganese, and soluble salts related to chlorides and nitrates of iron, copper, and cobalt, among other compounds (Monfort *et al*., 2014). Silica and colorants make up glaze. In order to lower the melting point of silica during the glaze manufacturing process, chemicals like lead, lithium, barium, sodium, and calcium are added as flux materials. Furthermore, it has been discovered that inhaling additional fluxing agents for glazes, such as those based on barium and lithium, is quite hazardous. Glaze components such as potassium carbonate, alkaline feldspar, soda ash, and fluorspar can cause skin irritation. Careless dipping, brushing, and pouring of certain glazes can potentially cause skin discomfort (Sfez *et al*., 2022). The inhalation of glaze smog during the spraying of the glaze mixture has the potential to create adverse health effects on workers. When glaze is processed, metallic compounds containing arsenic, beryllium, chromium, cadmium, nickel, and uranium are used to color the ceramic bodies. These compounds are known to cause cancer. In addition, severe toxicity originates from the inhalation of specific compounds of antimony, cobalt, barium, vanadium, lithium, and manganese to make glazes (Viana *et al*., 2017).

To safeguard employees from work-related accidents and illnesses, occupational health and safety are crucial to all aspects of ceramic manufacturing operations. Exposure prevention is the only way to prevent dust-related issues in the ceramic industry (Paluchamy & Mishra, 2022). It is necessary to conduct a health risk assessment for workers in the ceramic industry, given the hazards previously described. A health risk assessment is a screening tool that assists people in recognizing and comprehending their health risks as well as tracking their health over time. To identify issues crucial to a person's health and wellbeing in the ceramic industry, health risk assessments are also employed as part of the Medicare Annual Wellness Visit. They could also be used to identify people who require urgent medical attention while enrolling in Medicaid.

As a result, the initiative lessens the burden of dust-related occupational illnesses and calls for data based on dust exposure levels in the ceramics sector. The choice of method for this assessment depends to a large extent on the resources, the study's design, and what data are available. In the present study, the exposure levels of workers to respirable dust have been evaluated using the direct sampling method. Then, the non-carcinogenic hazards of dust will next be assessed using two risk assessment techniques: probabilistic risk assessment and deterministic risk assessment.

MATERIALS AND METHODS

Study area: This study focuses on the ceramic industries of Yazd province, located in the central region of Iran (Fig. 1). Yazd province has an area of about 76,469 km2, which alone covers four and a half percent of the total area of Iran. The ceramic industry is the most important industry in Yazd province in terms of job creation and economic development. The results of census studies have shown that the total number of ceramic industries in Yazd province is more than 189 units. Of these, 86 large ceramic industries are active. According to a general statistic of workers in Iran's industries, the population working in the ceramic industries of Yazd province is estimated to be around 300,000 people. It is estimated that the growth of ceramic production annually in Yazd province during the years 2013–2019 was 36%. The products of these units have a suitable quality on a global scale and are placed in the category of global average ceramics.

Production process for ceramics: A summary of the manufacturing process is shown in Figure 1. In ceramic production, there are two stages: shaping and glazing. Purchasing raw ingredients, making the slurry, forming, and drying are all part of the shaping stage. The glazing stage involves procuring raw materials, making the glaze-frit, milling, putting the glaze on the ceramic body, and firing (sinterization occurs during firing). When required, the ceramic is put through a finishing procedure that includes polishing and grinding before being picked and packaged. The sub-steps can be explained in the following way:

Preparation of raw materials (stage 1): The selection of raw materials, mostly carbonates, feldspars, and clays, as well as any necessary extraction and processing, constitute the initial step of the ceramic process (Sukhanova, 2024). After that, they are delivered to the ceramic

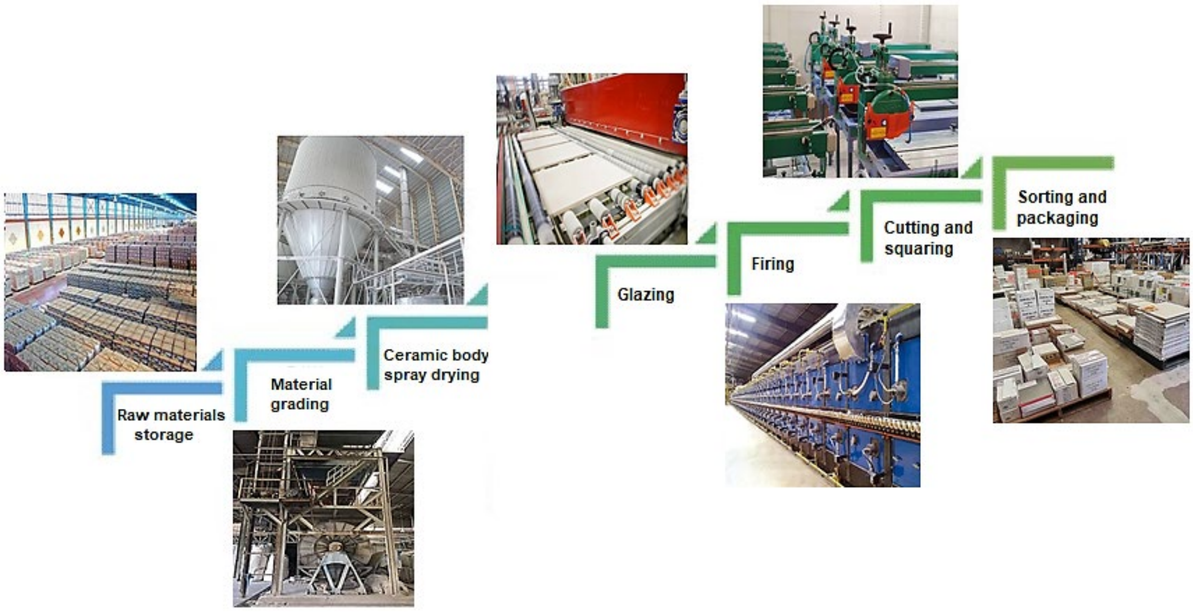

Fig. 1. Ceramic production process

factory, where they are kept until needed. Jaw crushers and hammers are used to reduce raw material to a size of 6 mm. These materials are then kept in silos for storage.

Preparation of granules (stage 2): A suspension is formed by mixing powdered materials with water in a mill. The result of this procedure is a suspension that was kept in agitation. Additions and glue are added to the suspension obtained before adding it to the ponds. Subsequently, spray dryers are used to turn the suspension into granules. The next step involves atomization, where the suspension is atomized and transformed into granular particles, which are also referred to as atomized powder.

Forming the "green" ceramic body (stage 3): The green ceramic body is formed by mechanical compression after the formation of this atomized powder. The bodies return to the dryer to completely dry at this stage and reach less than 1% of the water left in it. To do this, the ceramic piece is dried by subjecting it to the dryer's higher temperature, which is typically around 170 °C.

Glazing (stage 4): At the same time, glazes—glassy coatings—are being prepared to be put on the floor or tile surface. The primary input elements used in the process are the production raw materials (frits, kaolin, sand, pigments, different oxides, water, etc.), which are ground and combined to create an application-ready glaze (glaze suspension). Several techniques can be used to glaze the ceramic body, depending on the desired glazing surface appearance as well as the components' size, shape, number, and structure. These techniques include dipping, spraying, buzzing, curtaining, disking, dripping, and electrostatic application. After that, glazed bodies are kept in wagons to facilitate the initial drying processes. The ceramic production process is finished at this point. Once the humidity was lowered and the enamel coat was applied, the pieces were placed in kilns to undergo heat treatment at temperatures ranging from 800 °C to 1700 °C. In certain cases, the glaze coating is not the only decoration applied to the ceramics; a digital print is also used. The pieces are fed through printers, which usually use inkjet technology, and colored with inks that contain ceramic pigments to make a variety of decorative styles.

Grinding process and polishing (stage 5): Finishing is the broad term for post-firing processing, which might involve operations like polishing and grinding. The piece's edges are machined during the grinding process to make them parallel, perpendicular, and straight. Additionally, the piece's size is calibrated and controlled. The ceramic coating's surface is smoothed during the polishing process to eliminate irregularities and improve the surface's sheen.

Packing and packaging (stage 6): The coatings are then submitted to the classification phase, where their quality is taken into consideration and they are divided accordingly. The coating is then prepared for packaging and sale. The standard NBR 13817 (ABNT 1997b) employed a number of factors to classify ceramics, including the product's surface abrasion resistance classes, stain resistance grades, water absorption groups, shaping method, and surface appearance or visual analysis. These typologies' primary traits are extremely low porosity, homogenous structure, and water absorption.

Determining the sampling volume of respirable dust: The Similar Exposure Group (SEG) method was used to determine the sampling volume (Petit *et al*., 2017). SEGs are founded on the idea that employees should be grouped according to their job profiles, and their health risks should be evaluated according to similar exposure conditions. The purpose of using SEGs is to reduce data variability from exposure monitoring in order to make trustworthy assessments of health risks. After they are set up, they provide a more practical and comprehensible representation of job duties and activities at work, as well as the exposure hazards that go along with them. The SEG method provides a lot of advantages. SEGs are the cornerstone of any industrial hygiene program, to put it simply (Koivisto *et al*., 2021). Here are some reasons why the SEGs methodology might be chosen over other methods in the context of occupational epidemiology:

• Exposure homogeneity: SEGs make it possible to put workers together who have comparable exposure patterns and levels, which can help to lower exposure misclassification and raise exposure assessment accuracy. This can be crucial when researching how certain workplace hazards affect one's health.

• Statistical power: The SEGs approach can improve study statistical power by generating more homogeneous exposure groups. This is because it lessens the range of exposure levels that exist within each group, which facilitates the identification of possible correlations between exposures and health outcomes.

• Specificity in exposure-response correlations: By concentrating on groups with comparable exposure profiles, SEGs can assist researchers in identifying exposure-response correlations that are more precise. This can be helpful in figuring out exposure thresholds for harmful health effects and comprehending dose-response connections.

• Practicality and feasibility: Rather than attempting to evaluate individual exposures, it may be more feasible in many occupational situations to group workers based on similar exposure profiles. SEGs offer a useful method for describing exposure in huge occupational cohorts.

• Regulatory and policy considerations: Because SEGs offer a systematic and consistent method for describing and comparing exposures across various worker groups, their use may be in line with regulatory and policy requirements for occupational health and safety evaluations.

To implement this method, the following points were considered: 1) Similarity and regularity of the tasks carried out. 2) The materials and methods that are employed to accomplish tasks. 3) Similarity in how duties are carried out. According to these cases, workers can be placed in an exposure group (Koivisto *et al*., 2021). Two methods were used to identify SEGs: observation and sampling. The observation method is based on examining the activities performed by the workers and judging the expected similarity of the workers' exposure without using exposure monitoring information. In this method, four components are used: the process, job, task, and harmful chemical agent that take place in the workplace. In the sampling method, the exposure of a large number of workers to dust is measured, and then the measured information is statistically analyzed to assign SEG to each worker. Basically, an exposure group is classified as a SEG if 95% of the worker mean exposures fall within a factor of two or if the geometric standard deviation (GSD) of the exposure concentration distribution is less than 3. This method is called a quantitative approach.

When applying the SEGs technique in occupational epidemiology, the choice between the sampling and observation methods can be influenced by a number of factors, which may have an impact on the study's dependability. Qualitative information on the nature and context of exposures, including variables like length, frequency, intensity, and variability, can be obtained using an observational approach that may not be fully obtained through quantitative sampling alone. The observation method may be preferred in occupational settings where exposures are complex and heterogeneous, like the ceramic industry, because it enables a more thorough evaluation of the wide range of exposures that workers may encounter. This can be especially significant when exposures are difficult to capture using traditional sampling methods or when there are multiple concurrent exposures to take into account. Sampling techniques can yield useful quantitative data, but they might not fully reflect the complexity and diversity of exposures that employees encounter on a daily basis. In the present study, the observation method was used to identify SEGs. The observation method is an iterative process that takes time to fine-tune (Wang *et al*., 2021). These consist of a variety of techniques such as walkthroughs, interviews, field research, contextual inquiries, case studies, focus groups, and think-aloud protocols. This method was implemented by asking questions such as: What typical roles or jobs are assigned to employees? What are the duties they perform that could expose them to health risks? Exist any equipment or practices that vary that could affect the hazards of exposure when performing similar tasks? Which area of the manufacturing line exposes workers to the most dust during jobs or while they are working? In addition, the expertise of those with at least 15 years of experience in the ceramic industry was used to validate the validity of the observational method in order to more precisely detect SEGs.

Following an analysis of the workers' demographic data (age, work experience, smoking history, etc.), the participants in this study were chosen according to several criteria, such as: 1) workers who were exposed to dust most of the time; 2) workers who had at least five years of experience in the ceramic industry; 3) employees who were in excellent physical and mental condition and were not smokers; and 4) workers who worked almost 8 hours a day. In conclusion, out of the 500 workers that were exposed to respirable dust, 12 SEGs, each consisting of 15 to 27 workers, were formed. Based on the Rappaport and Kupper study, which recommended repeated samples from 5 to 10 randomly selected individuals per SEG, the number of personal dust samples was computed (Abaya *et al*., 2018). The sampling adequacy was then determined using the straightforward Eq. (1):

$$n \geq \frac{Z^2 . p(1-p)}{d^2} \tag{1}$$

where n is the sample size and Z is the value of the standard normal deviation corresponding to the level of confidence. For a 95% confidence level, the value of Z is 1.96. p is the number of samples taken in a preliminary study with a smaller sample size to get an idea of the expected value. d is the absolute precision, also called the margin of error (Sfez *et al*., 2022). A total of 240 workers were selected from the SEGs in order to collect personal air samples.

Measurement of respirable dust: Sampling from the respiratory zone is the most important sampling method because the sampled dust is in the vicinity of the worker's breathing zone. In this study, after determining the SEGs, samples were taken from the respiratory zones of the workers. The NIOSH 0600 technique was followed in the collection of breathing zone air samples (Barone *et al*., 2021). Using cyclones (SKC aluminum respirable cyclones) fitted with cassettes (SKC SureSeal three-piece 37 mm) carrying polyvinyl chloride (PVC) filters (SKC PVC filter 37 mm, 5.0 μm), the personal respirable dust samples were measured (Gendler *et al*., 2022). During the exposure period, the filters were placed in the volunteers' breathing zones and connected to an SKC AirChek 3000 sampling pump, which was programmed to provide a 2.5 L/min flow rate for four hours. After sampling the dust, the weight of the samples was obtained using an impeacher device. In this way, the weight of the filter was measured before and after the dust measurement. Then the dust concentration was determined using the following formula:

$$C = \frac{(W_2 - W_1) - (b_2 - b_1)}{V} \times 10^3 \quad (2)$$

C is the concentration of respirable dust (mg/m^3); W_1 is the weight of the filter prior to sampling (mg); W_2 is the filter weight after sampling (mg); B_1 is the weight of the control sample before sampling (mg); B_2 is the weight of the control sample after sampling (mg); V is the sampled air volume in liters (Seneviratne *et al*., 2024).

Theory of deterministic and probabilistic approaches to health risk assessment

Deterministic approach

Based on the mean values for input variables, deterministic risk characterization is computed (Fig. 2). In other words, when the exposure parameters (such as exposure duration, inhalation rate, etc.) are combined with C (exposure-point concentration, mg/kg) in risk assessment equations, the result is an estimate of the "reasonable maximum exposure," or the upper bound of the 95% confidence interval of the mean. The equations (3) and (4) were used to obtain the 95% upper confidence limit (UCL):

$$\text{If } (n \geq 30)\ UCL = X \pm Z\alpha/2 \times (\sigma/\sqrt{n}) \quad (3)$$

$$\text{If } (n < 30)\ UCL = X \pm Z\alpha/2 \times (\sigma/\sqrt{n}) \quad (4)$$

where x is the mean, σ is the standard deviation, α=1−(Confidence Level/100), Zα/2=Z-table value, tα/2=t-table value and UCL is the upper confidence limit (Shojaee Barjoee *et al*., 2023).

Probabilistic approach

Deterministic approaches inherently involve uncertainty, which might stem from differences in the surrounding environment as well as particular human qualities. Point values are typically input into a specific deterministic approach, ignoring the variability in the input variables and leading to biases in the outcomes of the subsequent human health risk assessment (Pervukhin *et al*., 2023; Taheri *et al*., 2022). Professionals in industry, government, and academia have developed, evaluated, and enhanced probabilistic models in order to more effectively recognize and understand the range of possible cumulative and aggregate exposures and health issues. A more practical method than the deterministic one is needed to address the issue of uncertainty and variability in the computation of human health risk. To achieve this, a probabilistic approach, i.e., the Latin hypercube sampling (LH_S) technique, was employed using Oracle Crystal Ball v11.1.2.4.850. (Fig. 2). LH_S is a way of generating random samples of parameter values. This technique uses a stratified sampling procedure to better cover the domain of variations in the input variables. When input variables are independent, this approach can be used (Iordanis *et al*., 2024). The foundation of the sampling process is the division of each variable's range into multiple intervals with equal probability. The goal is to estimate the following probability:

$$P_f = \int_{D_f} fX(x)dx = \int_{R^d} 1_{\{g(x)\leq 0\}} fX(x)dx = \mathbb{P}(\{g(x) \leq 0\}), \text{ if } D_f = \{x \in \mathbb{R}^d \mid g(x) \leq 0\} \quad (5)$$

The following is how the sampling procedure is executed: Each input variable's range is categorized into isoprobabilistic cells. A single cell is randomly selected from all the cells that

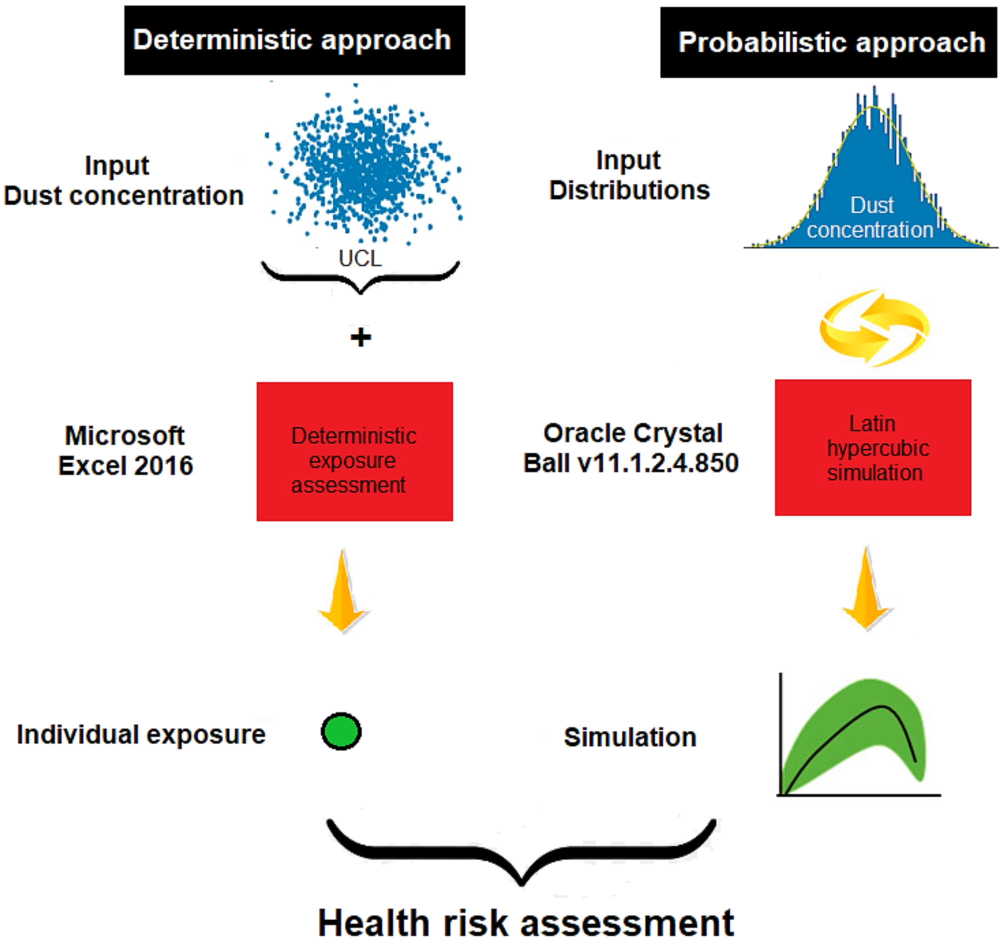

Fig. 2. Deterministic and probabilistic approaches in the health risk assessment

are accessible. In the selected cell, locally inverting the cumulative density function yields the random number. From the list of accessible cells, all the cells that share a stratum with the previous cell are removed. With LH_S, the probability of failure is estimated by:

$$\hat{P}^{n}_{f,\,LHS} = \frac{1}{n}\sum_{i=1}^{n} 1_{\{g(X^i)\leq 0\}} \tag{6}$$

where the sample of $\{X^i,\ i = 1\ldots n\}$ is obtained as described previously.

$$\mu_n = \frac{1}{n}\sum_{i=1}^{n} 1_{\{g(\underline{x}_i))\leq 0\}} \tag{7}$$

$$\sigma_n^2 = \frac{1}{n}\sum_{i=1}^{n} (1_{\{g(\underline{x}^i))\leq 0\}} - \mu_n)^2 \tag{8}$$

The estimator $\hat{P}^{n}_{f,\,LHS}$'s asymptotic confidence interval of order 1-α is:

$$\left[\mu_n - \frac{q_1 - \frac{\alpha}{2}.\sigma_n}{\sqrt{n}} ; \mu_n + \frac{q_1 - \frac{\alpha}{2}.\sigma_n}{\sqrt{n}} \right] \tag{9}$$

where q_1-α/2 is the reduced standard gaussian law N (0, 1)'s 1-α/2 quantile. It provides an objective estimate for P_f while emphasizing the need for independence in all input variables (van der Mensbrugghe, 2023).

The selection of probabilistic techniques, including LH_S and Monte Carlo approaches, is contingent upon various aspects, including the problem's dimensionality, the characteristics of the input parameter distributions, the available processing resources, and the analysis's particular objectives. The following are some possible benefits of LH_S:

• Enhanced sampling efficiency: Compared to simple random sampling, LH_S guarantees a more uniform coverage of the input parameter space, which can result in a more accurate representation of the input parameter space and a more effective use of computer resources.

• Diminished sampling variation: LH_S can assist in reducing the variation in the estimate of statistics or model outputs by guaranteeing that each input parameter gets sampled across its whole range without duplication.

• Improved input space exploration: LH_S makes it possible to explore the input parameter space more methodically, which is especially useful for studies on uncertainty quantification and sensitivity analysis.

• Application to high-dimensional issues: In high-dimensional issues where a more uniform coverage of the input parameter space is crucial, LH_S may prove to be more efficacious than a basic random sample (Iordanis *et al*., 2024).

Non-carcinogenic risk assessment: Following the determination of the workers' level of exposure to respirable dust, the USEPA technique was utilized to conduct a non-carcinogenic risk assessment (Shojaee Barjoee *et al*., 2023). To assess the health risk, first the amount of respiratory intake of the respirable dust was calculated using the exposure concentration (EC) parameter values according to Eq. (9):

$$EC = \left(C \times ET \times ED \times EF\right) / BW \times AT \tag{9}$$

where EC is the concentration of exposure (mg/m^3); C is the concentration of VA (mg/m^3); EF is the annual exposure frequency (for all groups: 345 days/year); ED is the exposure duration (years); ET is the exposure time for the worker (h/day^1); BW is the body weight (70 kg); AT is the average lifetime (for all groups: ED × 365 days). To calculate the non-cancerogenic risk associated with inhalational exposure to dust, the hazard quotient (HQ) was used, and calculations were performed according to Eq. (11):

$$HQ = EC / RfC \tag{11}$$

where HQ is the hazard quotient (unitless); EC is the exposure concentration (mg/m^3); and R*f*C is the reference concentration (mg/m^3). The exposed population is exposed to unacceptable risk if HQ falls higher than 1. However, the risk is classified as negligible or low if HQ falls below 1 (Gridina & Borovikov, 2022; Khodadadi *et al*., 2022).

All steps of probabilistic risk assessment using LH_S were performed in the Oracle Crystal Ball v11.1.2.4.850 program. To perform the LH_S, first, chi-square and Anderson-Darling tests were used to simulate the exposure factors' best-fitting probability distribution type. After 10,000 iterations, consistent exposure distribution findings were produced, and the probabilistic risk was evaluated using 95% confidence intervals of the mean of the results (Shojaee Barjoee *et al*., 2023). The sensitivity analysis was applied to identify how different input variables, which are determined based on the distribution function, differ in their values. If the number was positive, it meant that there was a positive correlation between the exposure factor and health risks; if not, there was a negative correlation. Sensitivity analysis was conducted in this study using six fundamental input variables: C, EF, ED, ET, AT, and BW. The range of each

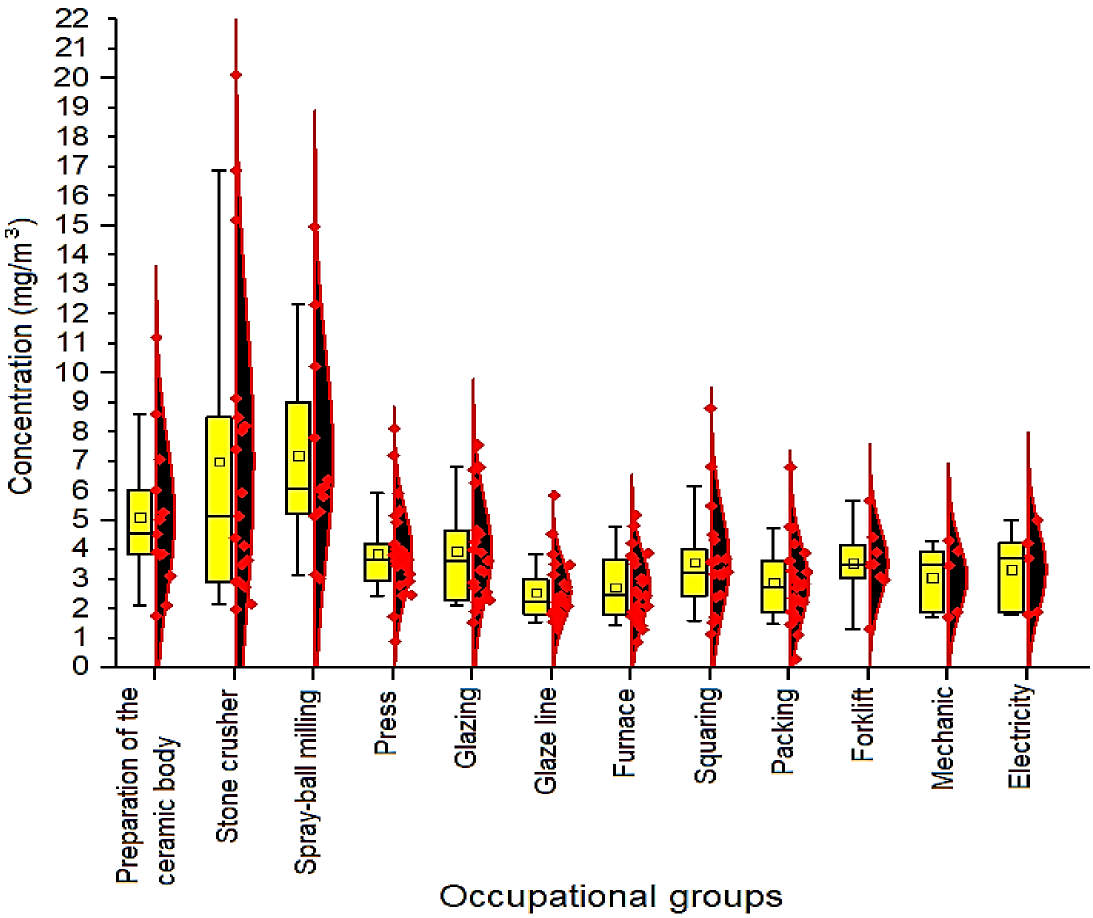

Fig. 3. Boxplots of respirable dust concentration in the studied occupational groups

factor was taken into consideration in this study as follows: EF was taken into consideration at 250 to 325 days/year; ED was 17 to 32 years; ET was 3 to 10.5 h/day; AT was 6205 to 11680; and BW was 60 to 75 kg.

Statistical analysis: All statistical analyses, such as maximum, minimum, average, standard deviation, coefficient of variation, t-test, and Kolmogorov-Smirnov tests, were conducted using IBM SPSS Statistics, version 23. In this study, a one-sample t-test was used to compare the values of respirable dust with American Conference of Governmental Industrial Hygienists (ACGIH) standard values (3 mg/m^3). In addition, the Kolmogorov-Smirnov (K. S.) test was used to assess the normality of respirable dust data. For all tests, the significance level was considered fixed at $\alpha = 0.05$.

RESULTS AND DISCUSSION

The results of respirable dust measurement in workers' respiratory zones using the SEG method are exhibited in Figure 3. The total concentration of respirable dust in the studied industry was measured at 820.03 mg/m^3. The maximum concentration of respirable dust was measured for the spray ball milling operator (14.97 mg/m^3) and the minimum for the packaging operator (0.28 mg/m^3). In terms of average respirable dust, occupational groups were arranged in the following descending order: spray-ball milling> crusher> preparation of the ceramic body> glazing> press> squaring> forklift> electricity> mechanic> packing> furnace> glaze line. The average concentration of respirable dust in the studied ceramic industry was measured

Table 1. HQ values obtained using the deterministic method

Operator	Min	Max	Mean	SD	Lower 95% CI of Mean	Upper 95% CI of Mean	Sample above 1 (n (%))
Preparation of the ceramic body	0.049	0.315	0.154	0,074	0.112	0.195	0 (0)
Stone crusher	0.002	0.475	0.167	0.123	0.108	0.226	0 (0)
Spray-ball milling	0.085	0.421	0.191	0.092	0.141	0.243	0 (0)
Press	0.025	0.229	0.107	0.043	0.091	0.125	0 (0)
Glazing	0.043	0.212	0.110	0.050	0.089	0.133	0 (0)
Glaze line	0.036	0.164	0.072	0.029	0.059	0.084	0 (0)
Furnace	0.024	0.146	0.076	0.033	0.063	0.090	0 (0)
Squaring	0.0324	0.248	0.100	0.051	0.076	0.124	0 (0)
Packing	0.007	0.91	0.080	0.039	0.065	0.096	0 (0)
Forklift	0.037	0.159	0.100	0.034	0.081	0.118	0 (0)
Mechanic	0.048	0.121	0.085	0.031	0.069	0.103	0 (0)
Electricity	0.050	0.140	0.093	0.037	0.073	0.114	0 (0)

at 4.06 mg/m^3. The average respirable dust in all occupational groups, except furnace, glazing line, and packaging, was higher than the values presented according to the ACGIH standard (3 mg/m^3). The K.S. test findings demonstrated that every occupational group's respirable dust data, with the exception of the stone crusher, press, glazing line, and packaging groups, had a normal distribution. The results of the t-test showed that there is a significant difference between the concentration values of respirable dust and the ACGIH standard value in the occupational groups of ceramic body preparation, stone crusher, spray ball milling, press, glazing, and glazing line. In each occupational group, at least 34% of the dust samples collected had a concentration greater than the ACGIH standard. The operators responsible for spray-ball milling and ceramic body preparation had the highest frequency of dust samples, more than the ACGIH standard. In the meantime, the most respirable dust was collected for the stone crusher occupational group. Also, the highest variation coefficient was measured for this occupational group.

Deterministic risk assessment: The results of the deterministic risk assessment for the studied occupational groups are shown in Table 1. For every occupational group, non-cancer risk values less than 1 were found, indicating tolerable non-cancer risks across the board. Overall, none of the samples had an estimated HQ value greater than 1. The highest mean HQ values were predicted for the spray ball milling group. The lowest was calculated for the glaze line group.

Probabilistic risk assessment: The results of probabilistic risk assessment using the Latin hypercube method are shown in Figure 4. The probabilistic risk assessment's findings demonstrated that the value of HQ is greater than one in some samples for a few task groups, including forklifts, ball milling sprays, and stone crushers. Non-cancer risks are anticipated to arise in these occupational groupings, nevertheless.

Figure 5 compares the outcomes of probabilistic and deterministic approaches. There is a strong correlation between the outcomes of these two approaches, as indicated by the reported correlation coefficient of 0.95. Additionally, compared to the deterministic approach, the results of the probabilistic risk assessment were projected to be higher in some occupational groups.

Sensitivity analysis: The most pertinent input data can be evaluated using sensitivity analysis for determining the non-carcinogenic risk assessment of respirable dust in the exposed population. Figure 6 displays the findings of the sensitivity analysis of influencing factors on non-cancer risks. The findings indicated that the non-cancer risks are positively impacted by four factors: C, ET, ED, and EF. The concentration of respirable dust was one of the most effective factors that indicated a considerably higher potential non-carcinogenic risk for occupational groups than factors such as ET, ED, EF, BW, and AT. The "concentration of respirable dust" factor in this study contributed 60.4% to HQ in occupational groups. The contributions of three factors, ET, ED, and EF, to non-cancer risks were predicted to be 26, 6.3, and 1%, respectively.

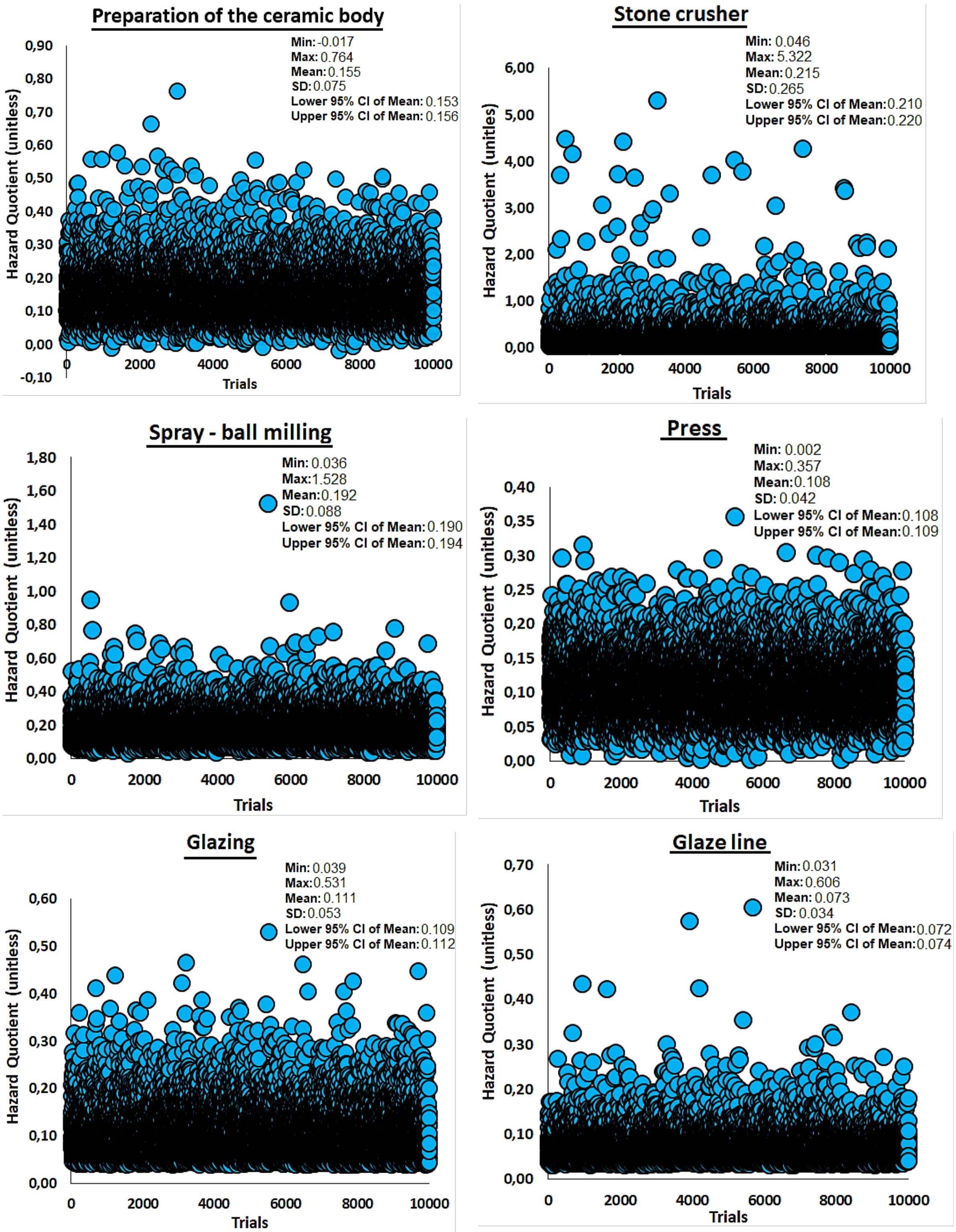

Fig. 4. HQ values for occupational groups using the Latin hypercube method

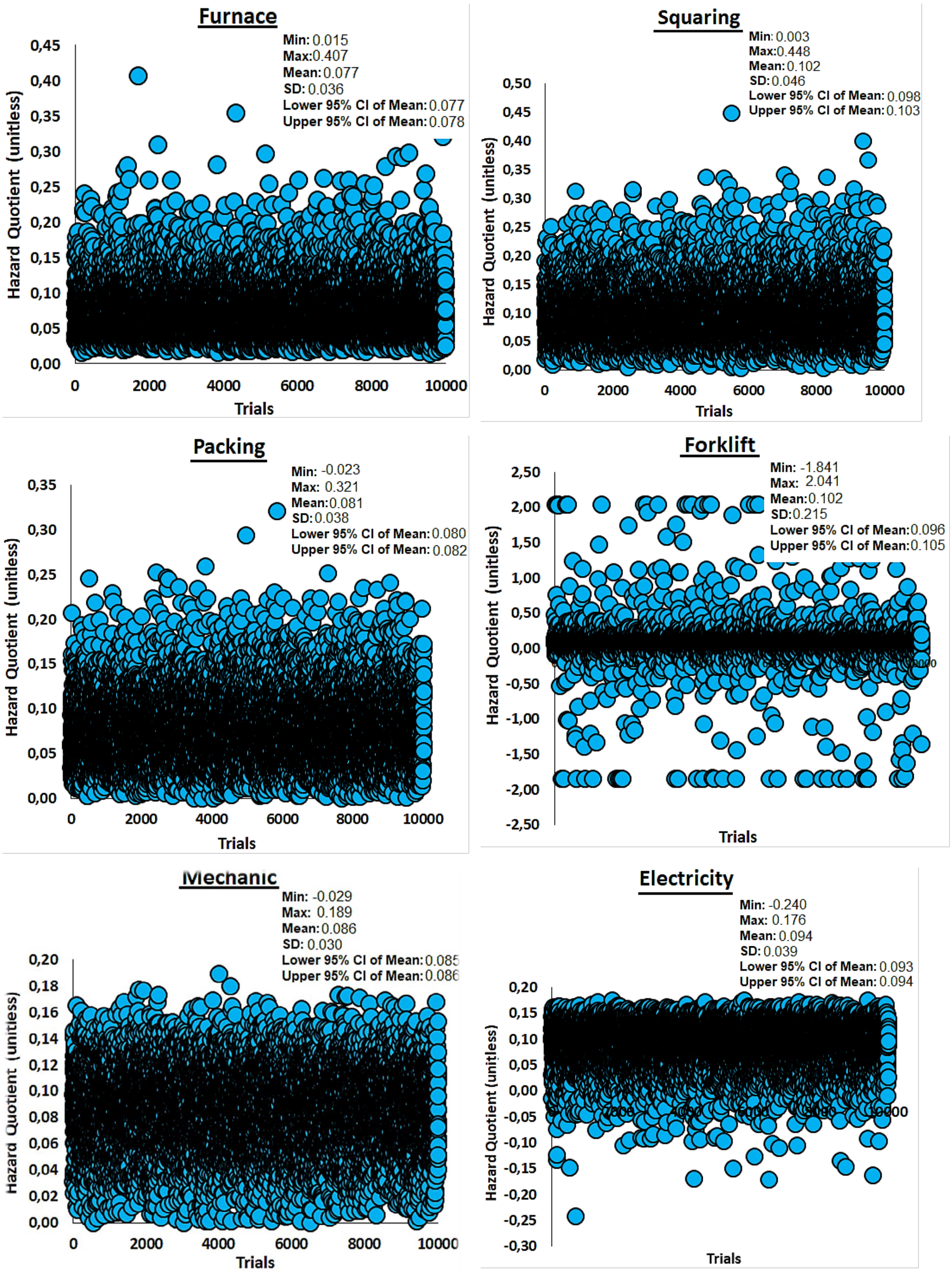

Fig. 4. HQ values for occupational groups using the Latin hypercube method

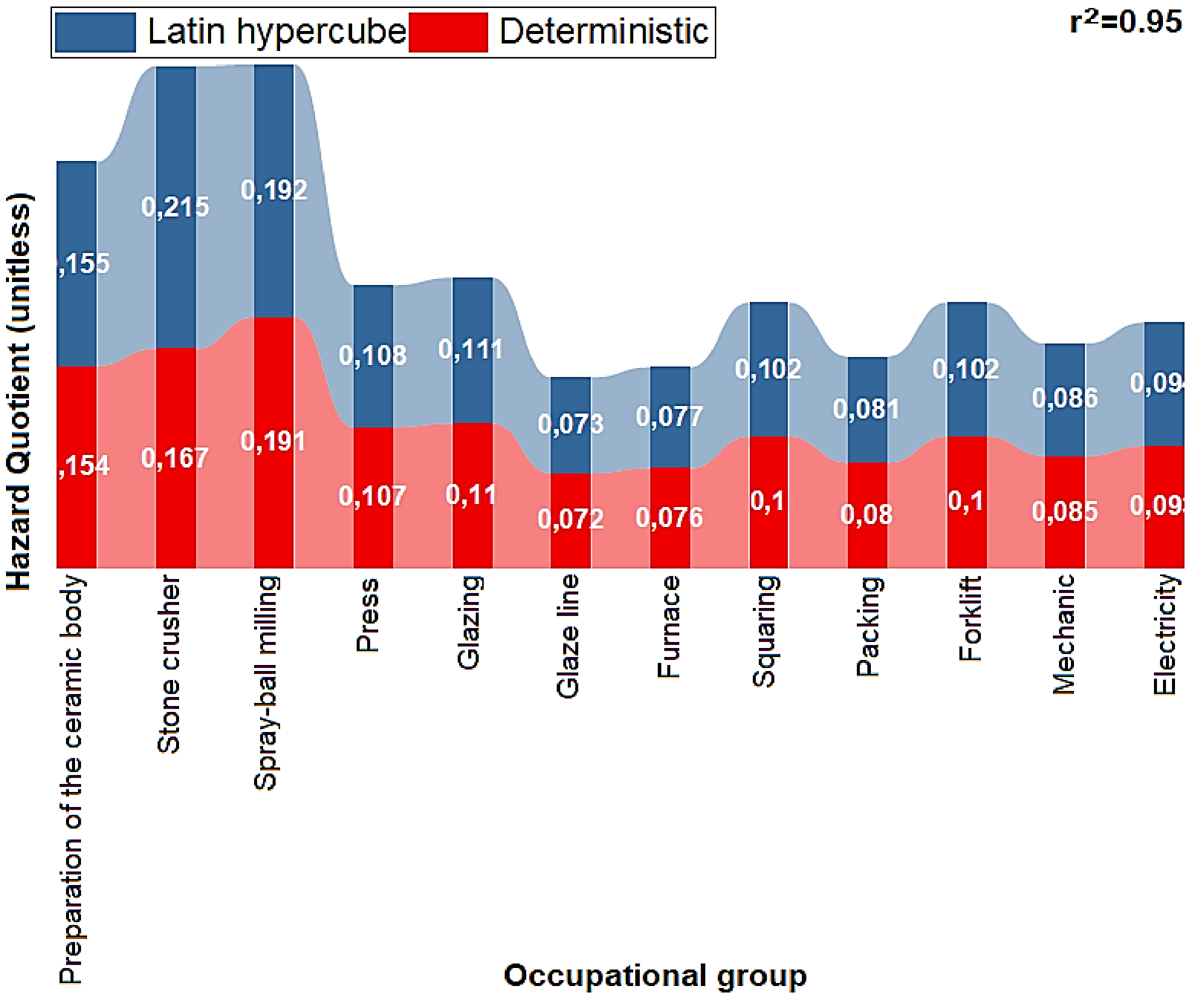

Fig. 5. Correlation between two deterministic and probabilistic risk assessment methods

Furthermore, the findings demonstrated a negative relationship between BW, AT, and non-cancer risks. It was found that the AT and BW factors contributed -5.8 and -0.6%, respectively, to non-cancer risks.

The prevalence of distinct dust fractions in particular types of industries has been the subject of numerous studies and discussions. These studies frequently contrast the effectiveness of various measuring systems or the conversion factors between "total" and "inhalable" dust in particular industry types (Kolvakh K. A., 2023; Kornev *et al*., 2022). Only a limited number of studies have focused on the conversion of inhalable to respirable dust. It has been utilized in certain research to evaluate exposure using worker job histories, worker occupational histories, or worker surveys. In other research, researchers have employed quantitative assessment techniques that include collecting samples from the breathing region of employees, doing stationary air sampling, drawing blood and urine samples, and measuring the levels of enzymes that indicate the degree of exposure over a given amount of time. In this study, workers' breathing regions were directly measured in order to assess their exposure to respirable dust using the SEGS approach. The respirable dust exposure measurements in this survey were restricted to one dust monitoring shift at thirteen specifically chosen ceramic industry workplaces. The current study measured the respirable dust value within the range of 0.28 to 20.13 mg/m^3. Workers were exposed to respirable dust levels far above the then-current ACGIH limit when they performed dry work without the use of wet dust suppression or other dust minimization

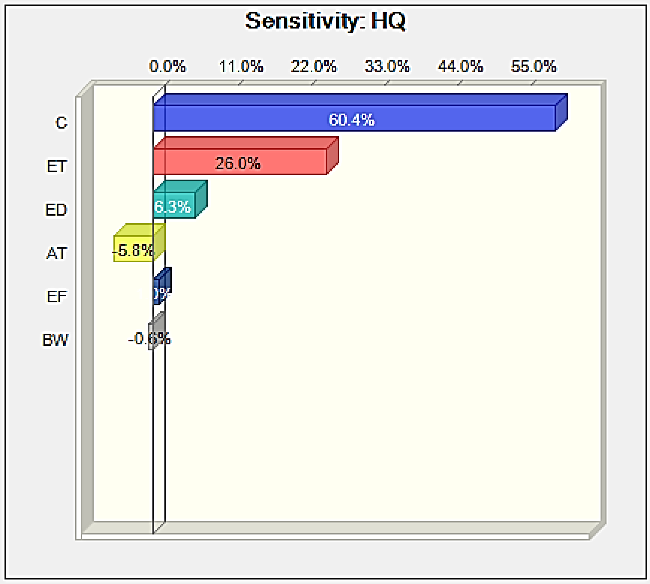

Fig. 6. Sensitivity analysis of influencing factors on non-cancer risks

techniques. Some workers also performed wet work with the stone. Most workers performing tasks involving the glazing and firing of ceramic bodies or packaging had lower respirable dust levels. However, a few work samples also showed high respirable dust levels. They were recognized as laborers who prepared raw materials, made powder from slurry, formed or pressed powder, and cut ceramic edges with a laser. They either disregarded or lacked safety obstacles, such as fencing. Additionally, the majority of these operators lacked any kind of respiratory protection gear. In order to eliminate respirable dust, all of the workplaces studied depended on pedestal or wall fans and natural ventilation from open doors. There were no engineering controls in any of the workplaces, but the local exhaust ventilation (LEV) systems were found to be ineffective because they were not properly constructed for the work environment and had badly maintained, overloaded filters.

Though respirable dust in the ceramic industry has not been the subject of many studies to date, a more accurate assessment of the industry's air quality can be gained by contrasting it with other industries that share similar manufacturing methods. The average respirable dust exposure in the cement industry, according to Thai *et al.*'s examination of a cement grinding facility in Ho Chi Minh City, was 4.67 mg/m^3, which was higher than the average respirable dust concentration found in the current study (4.06 mg/m^3) (Thai *et al.*, 2021). In another study conducted by Omidianidost *et al.* on 283 workers in the cement industry, the concentration of respirable dust was reported in the range of 1.77 to 6.12 mg/m^3, which was lower than the concentration range of respirable dust obtained in the present study (0.28 to 20.13 mg/m^3) (Omidianidost *et al.*, 2019). Otgonnasan *et al.* reported a mean concentration of respirable dust among copper mine workers located in Mongolia of 0.35 mg/m^3 (Otgonnasan *et al.*, 2022).

Non-cancer risks refer to the potential adverse health effects that are not related to the development of cancer. Non-cancer risks encompass a wide range of health concerns, including respiratory problems, neurological effects, reproductive issues, and developmental disorders. Estimates of the risks to human health based on risk assessments are dependent on a number of factors, including body weight, respirable dust concentrations, and other factors that can vary from person to person or location to site (Hosseinzadeh *et al.*, 2023). A way to "quantify" uncertainty is required in order to take into consideration the uncertainty that each parameter may add to the estimate. In modeling, sensitivity analysis and risk assessment are essential components of Latin hypercube simulation. The process of sensitivity analysis aids in evaluating how responsive the model's outputs are to variations in the input variables, and risk assessment helps decision-makers recognize and control possible hazards related to the virtual results. In this study, the risk of workers being exposed to respirable dust in their respiratory systems was evaluated using two probabilistic and deterministic approaches. Deterministic risk assessments provide a single point estimate of risk at a place of concern, whereas probabilistic risk assessment methodologies generate a range of values from probability distribution functions (PDFs). The results of the deterministic technique's risk assessment in this study did not demonstrate complete compliance with the probabilistic method ($r^2 = 0.95$). In the probabilistic risk assessment method, some occupational groups were predicted at unsafe levels in a number of samples. Therefore, the possibility of respiratory problems, neurological effects, reproductive issues, and developmental disorders is high in some occupational groups, especially in stone crushers. The results of this study are in line with a study by Kayembe-Kitenge *et al*. that found that respiratory symptoms were common among stone crusher workers (Kayembe-Kitenge *et al*., 2020). Additionally, the results of a study on pulmonary issues among 240 workers at a stone-crushing industrial site in Bangladesh indicated that respiratory symptoms like coughing, chest pain, and wheezing are frequently seen (Kabir *et al*., 2018). In the risk assessment by the deterministic method, the HQ values were predicted at safe levels for all occupational groups. Because deterministic approaches rely on averages, the projections they produce are in the in the conservative upper 95th percentile ranges. Deterministic risk assessment has some drawbacks, one of which is that the calculated risk is an average risk estimate rather than a range of expected risk at a site. The range of risk values and the conservatism of the risk estimate that probabilistic risk assessment models offer make them useful. By offering a range of potential risks present at a site and the degree of conservatism in the risk assessments, probabilistic risk estimates can make sense improvements to deterministic risk assessment techniques and can enhance risk management decisions.

Regarding the possibility of an adaptive monitoring approach, the characteristics of respirable dust necessitate risk management to look beyond the single-hazard perspective and instead address a more comprehensive systemic view (in time and space) that can take into account different exposure pathways, value considerations, and cross-sectoral governance arrangements to facilitate adaptation (Bazaluk *et al*., 2024). Maybe risk management is too difficult by nature to have a great general solution. Consequently, risk management ought to be viewed as a continuous procedure as opposed to a final goal. Current international regulations do offer general guidelines for managing emerging risks; these include the ISO/TS 31050:2023 guideline (which was expanded from the ISO 31000 guideline with recommendations) (Liu *et al*., 2024). These guidelines emphasize the need to continuously review emerging risks as they emerge and to take into account a wide range of potential future scenarios. First and foremost, historical data, conceivable exposure situations, and long-term effects should all be taken into account when determining the appropriate degree of protection. Risk management ought to be flexible enough to allow for the tracking of management actions in tandem with shifts in the variables affecting risks. Tracking and upgrading respirable dust controls can benefit from measures like calculating the exposed population or keeping an eye on growing respirable dust disturbance activities (Bazaluk *et al*., 2024). In terms of ownership, size, scale, disturbance and exposure circumstances, and populations most exposed, the choice of respirable dust controls offers some flexibility in the application of the risk management process. For instance, among the risk reduction strategies for respirable dust are restricting: engineering controls, administrative control, and development of safety culture (Anlimah *et al*., 2023).

By erecting a physical barrier—such as machine guards, industrial cleaning equipment, covered or enclosed conveyors, and curtains—between the worker and the hazard, engineering controls may be able to efficiently lower concentrations of respirable dust (Korshunov *et al*., 2023). Air scrubbers and air purification systems are a combination of filters and air purification technologies that can reduce the concentration of respirable dust in the workplace by up to 90%. An industrial sweeper is a mechanized device that is used to collect dry pollutants and dust from floor surfaces. When a high-pressure misting system is used in workplaces, tiny water droplets (less than 10 microns in diameter) fall to the ground and pick up dust particles that are the same size. This clears the air of suspended particles and creates a hygienic and safe working environment. While engineering controls are a useful tool for reducing exposure risk, their initial costs are typically higher than those of administrative controls or personal protective equipment (PPE) since they may need to replace or modify current equipment (George *et al*., 2023; Seregin *et al*., 2022). On the other hand, in the long run, they are economical. Creating awareness, scheduling routine equipment maintenance, teaching employees about the risks associated with respirable dust, and giving them the best management techniques for controlling and tracking their exposure to respirable dust are a few examples of administrative controls. Accurate risk perception results in safer workplace behavior; hence, it is imperative for worker protection to be aware of potential health hazards and available preventive measures. Training of workers in the ceramic industry (Shestakova & Morgunov, 2023).

Employers can also use exposure plans to educate staff members about the possible risk of breathing in respirable dust and to offer mitigation strategies. Employers and employees would have a better understanding of the risks and effects of exposure within their industry and occupation by examining and training these exposure plans. To provide worker protection, it is essential for the employer to foster a culture where employees are routinely involved in risk mitigation and prevention. Employees are more likely to take risks and respond by displaying behaviors like absenteeism and low dedication if they believe their sense of risk regarding their health and safety at work is disregarded (Sifanu *et al*., 2023). Regular safety meetings with employee engagement can also aid in the generation of fresh concepts for risk reduction. Employers may notice an increase in employee buy-in by involving staff members in the creation and implementation of safety procedures, since these staff members are more likely to embrace changes that are made for the better. Employee involvement may encourage them to take personal responsibility for their safety or to speak up when they witness coworkers not following safe work practices or wearing PPE.

The results of this study on occupational hygiene were also helpful to the regulator in creating an intervention program for the ceramic industry. Thus, before safe work regulations were implemented, these findings might be used to comprehend typical work practices and potentially, typical respirable dust exposures among the majority of ceramic industrials. When examining occupational diseases cases involving workers who have previously worked in the ceramic industry, this information will be helpful in establishing a correlation with prior high respirable dust exposures.

CONCLUSION

The primary purpose of this study was to evaluate the respirable dust levels in ceramic industries in central Iran and assess the corresponding risk of non-carcinogenic. The average respirable dust in all occupational groups, except furnace, glazing line, and packaging, was higher than the values presented according to the ACGIH standard. The levels of non-cancer risks were predicted in a safe range using a deterministic method. The probabilistic risk assessment's findings indicated that various occupational categories, including spray ball milling, stone crushers, and forklifts, may have non-cancer risks that are too high. The concentration of respirable dust and exposure duration were the two most significant factors affecting non-cancer risks, according to the results of the sensitivity analysis of those components. In general, it can be stated that regulators can create and modify targeted intervention plans in the ceramic industrial with the use of data gathered from the monitoring of respirable dust levels and related health risks in this study. The risk methodologies utilized in this study can be applied by those with low resources to create exposure prevention programs and help identify occupational diseases in sensitive working populations early on. The industry studied in this evaluation uses raw materials that contain high concentrations of silicates and may expose workers to high concentrations of respirable silica above the occupational exposure limit. We suggested putting in place a program or control mechanism to stop recurrent excessive respirable dust exposures. Furthermore, in cases where source controls are insufficient to maintain exposures below occupational exposure limits or until such controls are implemented, proper respiratory protection should be employed. To comply with the requirements of the Occupational Health and Safety Regulation (OSHR), employers must update their exposure control plans on a regular basis. By actively developing a positive safety culture through regular safety meetings, policy and procedure reviews, and engagement from all organizational levels, it is possible to improve employee risk perception and hazard awareness. Work safety specialists should employ every instrument at their disposal to address the issue, such as improving local exhaust ventilation, equipment redesign, active dust suppression techniques, and the temporary use of respiratory protective equipment. Therefore, future research directions on respirable dust exposure control in ceramic industry should focus on the following issues: (1) longitudinal studies to observe long-term health outcomes; (2) development of advanced engineering control methods considering the economic conditions of the industry; (3) a study on the qualitative fitting properties of facepiece respirators with filters for workers in the ceramic industry; (4) comparing the efficacy of different dust control measures across various ceramic industries; (5) design of the local exhaust hoods to reduce the amount of respirable dust produced during the powder preparation process.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been thoroughly observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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