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# OCCUPATIONAL DUST EXPOSURE AND PULMONARY FUNCTION IMPAIRMENT IN MANUFACTURING FACILITIES

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## ABSTRACT

***This cross-sectional analytical study investigated occupational dust exposure and its association with pulmonary function among workers in manufacturing facilities. Environmental monitoring was conducted across five factories using standardized gravimetric sampling techniques under controlled laboratory conditions. Dust concentration (mg/m³) and 8-hour Time-Weighted Average (TWA) values were calculated and compared between measurement rounds, with focused comparative analysis between Factory B and Factory C due to observed exposure variability. Spirometric assessment was performed according to ATS/ERS 2019 standards to evaluate Forced Vital Capacity (FVC), Forced Expiratory Volume in one second (FEV1), and the FEV1/FVC ratio. Results demonstrated that most factories showed relatively stable dust concentrations without statistically significant differences between measurement rounds. However, Factory C exhibited a statistically significant increase in measured dust concentration ($p = 0.04$), with marked variability suggesting instability in environmental control systems. Pulmonary function analysis revealed that exposed workers had significantly lower predicted FVC% and FEV1% compared to controls ($p < 0.05$). Pearson correlation analysis identified statistically significant positive associations between dust exposure metrics (measured concentration and TWA) and pulmonary function parameters ($r = 0.482–0.614$, $p \leq 0.005$), while no significant correlation was observed with the FEV1/FVC ratio. The findings emphasize the importance of continuous exposure monitoring, engineering control evaluation, and routine respiratory surveillance. Factory-specific***

***exposure variability may significantly influence respiratory health outcomes, underscoring the need for targeted intervention strategies to reduce occupational dust-related risks.***

**KEYWORDS:** Occupational Dust Exposure, Respirable Particulate Matter, Time-Weighted Average (TWA), Pulmonary Function, Spirometry, Manufacturing Facilities, Exposure Variability.

## 1. INTRODUCTION

Occupational exposure to airborne dust remains one of the most significant environmental hazards affecting industrial workers worldwide. Dust generated during manufacturing processes such as cutting, grinding, drilling, crushing, and polishing contains respirable particles that may penetrate deep into the pulmonary system and cause progressive respiratory impairment (World Health Organization [WHO], 2022). Industrial dust exposure has been strongly associated with reduced lung function parameters, chronic obstructive pulmonary disease (COPD), pneumoconiosis, and other occupational lung disorders (NIOSH, 2021).

Respirable particulate matter smaller than 10 micrometers (PM10) and especially particles smaller than 2.5 micrometers (PM2.5) are capable of bypassing upper airway defense mechanisms and depositing in alveolar regions (Pope & Dockery, 2006). Prolonged exposure results in inflammatory responses, oxidative stress, and airway remodeling (Kampa & Castanas, 2008). Several studies have demonstrated that workers in stone processing, cement industries, mining, and construction sectors experience significant reductions in Forced Vital Capacity (FVC) and Forced Expiratory Volume in one second (FEV1) compared to non-exposed controls (Meo et al., 2013; Ulvestad et al., 2001).

Gravimetric dust sampling remains the gold standard for occupational exposure assessment, allowing accurate calculation of airborne concentration in $mg/m^3$ (OSHA, 2020). Additionally, the 8-hour Time-Weighted Average (TWA) provides a standardized estimate of daily exposure levels and is widely used for regulatory compliance (ACGIH, 2023).

This study investigates dust exposure levels across five manufacturing facilities and evaluates their association with pulmonary function impairment using standardized exposure measurement and spirometric testing.

The relationship between occupational dust exposure and pulmonary dysfunction has been extensively documented in occupational epidemiology. Chronic inhalation of mineral and organic dust particles can initiate inflammatory cascades within the respiratory tract, leading to fibrosis, airway narrowing, and impaired gas exchange (Balmes, 2019). Occupational exposure has been linked not only to restrictive lung patterns but also to obstructive airway diseases depending on the particle composition and exposure duration (Blanc et al., 2019).

Studies conducted among marble and granite workers revealed statistically significant reductions in predicted FEV1% and FVC% values compared with administrative staff serving as controls (Mwaiselage et al., 2005). Similarly, research among cement factory workers demonstrated a dose–response relationship between cumulative dust exposure and decline in lung function parameters (Neghab & Choobineh, 2007). These findings highlight the importance of both exposure intensity and duration in determining respiratory outcomes.

Environmental monitoring under controlled temperature and humidity conditions enhances the reliability of gravimetic measurements (Hinds, 1999). Repeated weighing of filters before and after sampling minimizes systematic measurement errors and improves precision in estimating particulate mass concentration.

Although regulatory bodies such as OSHA and WHO have established permissible exposure limits (PELs), variability within industrial facilities remains common due to differences in engineering controls, ventilation systems, and operational practices (OSHA, 2020; WHO, 2022). Therefore, site-specific exposure assessment is essential for identifying high-risk environments.

This research aims to quantify dust exposure levels and analyze their statistical association with pulmonary function impairment among exposed workers.

Understanding intra-factory variability in dust concentration is critical for effective occupational risk management. Previous research has shown that even within the same industrial sector, exposure levels may vary significantly between facilities due to differences in equipment maintenance, dust suppression systems, and work practices (Tjoe-Nij et al., 2010). Such variability may lead to episodic peaks in exposure that are not captured by average daily measurements but may still contribute to cumulative lung damage.

The 8-hour Time-Weighted Average (TWA) remains a regulatory standard; however, short-term fluctuations can influence biological responses differently than steady exposure (Seixas et al., 2004). Therefore, combining descriptive exposure statistics with correlation analysis against physiological markers provides deeper insight into occupational health impact.

Spirometry is widely recognized as a reliable, non-invasive method for assessing respiratory impairment in occupational health surveillance programs (American Thoracic Society, 2019). Declines in FVC% and FEV1% may indicate

restrictive or obstructive lung patterns depending on their relationship with the FEV1/FVC ratio.

By integrating exposure measurement with pulmonary assessment, this study contributes to evidence-based occupational health monitoring. It further evaluates statistical correlations between measured/calculated dust concentrations and lung function indices, offering insight into potential physiological consequences of industrial dust exposure.

## 2. LITERATURE REVIEW

Occupational dust exposure is a major health concern in industrial sectors such as stone cutting, cement production, and mining. Prolonged inhalation of respirable dust has been shown to reduce lung function parameters, including **Forced Vital Capacity (FVC)** and **Forced Expiratory Volume in one second (FEV1)** (Blanc et al., 2019; Balmes, 2019). Workers exposed to silica-containing dust in marble and granite industries often exhibit significantly lower predicted FEV1 compared with non-exposed controls (Mwaiselage et al., 2005). **Respirable crystalline silica (RCS)** is particularly hazardous and classified as a **Group 1 carcinogen** linked to lung cancer and silicosis (IARC, 2012). Importantly, lung function decline may occur even before clinical symptoms or radiographic abnormalities appear (NIOSH, 2021).Steenland et al. (2001) reported measurable lung function decline among workers exposed to silica concentrations considered compliant with regulatory standards. This evidence highlights limitations of relying exclusively on threshold-based regulatory frameworks. Continuous environmental monitoring, periodic spirometric assessment, and proactive exposure control strategies are therefore essential to prevent cumulative respiratory damage in industrial workers.

Research within cement manufacturing industries demonstrates that inhalable and respirable dust fractions have differential impacts on pulmonary health. Neghab and Choobineh (2007) observed significant reductions in FEV1% and FVC% among exposed workers, with impairment correlating to years of service. These results support the hypothesis that exposure duration intensifies respiratory decline.

In mining sectors, occupational exposure to mineral dust has consistently been associated with measurable alterations in pulmonary function. Several studies indicate that miners frequently develop restrictive ventilatory patterns, characterized primarily by reductions in predicted Forced Vital Capacity (FVC%) without significant evidence of airflow obstruction (Meo et al., 2013). Restrictive impairment reflects reduced lung expansion capacity, often resulting from parenchymal fibrosis or interstitial inflammation caused by prolonged dust deposition within the alveolar regions. Unlike obstructive patterns, which are defined by reduced FEV1/FVC ratios, restrictive patterns typically preserve the ratio while demonstrating decreased lung volumes. This distinction is clinically important, as it reflects different underlying pathophysiological mechanisms linked to dust composition and exposure duration.

However, the respiratory impact of occupational dust exposure varies according to particle characteristics. In environments where dust consists of mixed mineral and organic particles, or includes combustion-derived particulates, obstructive changes may also develop (Blanc et al., 2019). Organic dust components, endotoxins, and fine particulates can provoke airway hyperresponsiveness and chronic bronchial inflammation, contributing to airflow limitation and reduced FEV1. Therefore, exposure composition significantly influences the resulting respiratory pattern.

Airborne particulate matter smaller than 2.5 micrometers (PM2.5) presents particular concern due Fine particulate matter such as **PM2.5** can penetrate deeply into the alveoli, bypassing normal respiratory defense mechanisms and triggering inflammatory responses in lung tissues (Pope & Dockery, 2006). Chronic exposure increases oxidative stress, stimulates inflammatory cytokines, and contributes to airway remodeling and impaired gas exchange (Kampa & Castanas, 2008). Research also shows that **short-term exposure peaks** may produce stronger biological effects than stable moderate exposures, even when daily time-weighted averages appear similar (Seixas et al., 2004; Steenland & Ward, 2014). Therefore, combining **gravimetric dust measurements with statistical analysis** and considering exposure variability across workplaces is essential for accurate occupational risk assessment (ACGIH, 2023; WHO, 2022).

Gravimetric sampling remains the reference method for quantifying airborne dust concentration in occupational environments; however, its accuracy is highly dependent on strict environmental control during filter conditioning and weighing procedures. Hinds (1999) emphasized that fluctuations in temperature and relative humidity can alter filter mass through moisture absorption or desorption,

thereby introducing systematic measurement errors. Even minor variations in environmental conditions may influence pre- and post-weight measurements, potentially leading to overestimation or underestimation of particulate concentration. For this reason, standardized conditioning protocols under controlled laboratory conditions are essential to ensure reproducibility and precision in dust exposure assessment.

The **World Health Organization (WHO)** recommends repeated sampling in occupational exposure assessment to capture day-to-day variability in airborne dust levels, since single measurements may underestimate exposure peaks (WHO, 2022). Long-term cumulative exposure to industrial dust, particularly **respirable crystalline silica**, has been strongly associated with progressive lung function decline and increased risk of **chronic obstructive pulmonary disease (COPD)**, even among non-smokers (Steenland & Ward, 2014). Studies in stone-cutting industries show that workers exposed to silica dust experience significant reductions in **FEV1 and FVC**, especially where ventilation and dust-control systems are inadequate (Mwaiselage et al., 2005). Therefore, **continuous monitoring, spirometric surveillance, and preventive exposure controls** are essential to protect respiratory health.

Regulatory agencies such as OSHA (2020) have lowered permissible exposure limits for respirable crystalline silica to reduce long-term health risks. However, compliance does not eliminate exposure variability within shifts.

Exposure response modeling indicates that incremental increases in dust concentration are associated with measurable decreases in lung function parameters (Blanc et al., 2019). This supports the use of correlation analysis in evaluating occupational health outcomes.

Pulmonary function testing remains a cornerstone of occupational health surveillance. The American Thoracic Society (2019) standardizes spirometry procedures to ensure reproducibility and diagnostic accuracy.

Declines in predicted FVC% may indicate restrictive impairment, while reductions in FEV1% may suggest obstructive or mixed patterns (ATS, 2019). Occupational dust exposure has been linked to both patterns depending on particle type and exposure intensity.

A meta-analysis by Fishwick et al. (2015) found significant associations between workplace dust exposure and chronic airflow limitation. Similarly, Cullinan et al. (2017) reported increased COPD prevalence among industrial workers with long-term dust exposure.

Correlation-based studies emphasize that even moderate exposure levels may affect predicted lung function percentages before clinical symptoms manifest.

The 8-hour Time-Weighted Average (TWA) remains a central regulatory benchmark in occupational hygiene and is widely adopted to evaluate worker exposure relative to established threshold limit values (ACGIH, 2023). The TWA represents the average airborne concentration of a hazardous substance over a standard work shift and serves as the basis for compliance with permissible exposure limits. While this metric provides a standardized framework for exposure assessment, it may not fully capture the biological implications of fluctuating or peak exposures. Seixas et al. (2004) argued that reliance exclusively on TWA can underestimate true health risks, particularly in environments where short-term concentration spikes occur. Such peaks may trigger acute inflammatory responses and oxidative stress, even if the daily average remains within acceptable limits.

Occupational research demonstrates a strong **dose–response relationship** between dust exposure and lung function decline, with higher cumulative exposure associated with reductions in **FEV1 and FVC** (Neghab & Choobineh, 2007). In granite and stone processing industries, exposure to **respirable crystalline silica** and mixed mineral dust has been linked to pulmonary injury, systemic inflammation, and increased risk of **chronic obstructive pulmonary disease (COPD)** (Blanc et al., 2019; Steenland & Ward, 2014). Accurate occupational risk assessment therefore requires integrating **gravimetric dust measurement with spirometric monitoring**, while accounting for exposure variability and short-term concentration peaks that may intensify respiratory damage (WHO, 2022; Burstyn & Teschke, 2015).

Industrial operations such as cutting, crushing, and polishing often generate episodic dust peaks depending on workflow intensity and machinery conditions (Hoy et al., 2018). Studies in construction and mineral processing industries demonstrate that task-based exposure measurement reveals substantial within-shift variability that is not adequately reflected by 8-hour averages (Doney et al., 2020). Furthermore, exposure heterogeneity complicates risk characterization. Research indicates that workers performing high-dust tasks intermittently may accumulate greater biological burden compared to workers with constant moderate exposure (Rappaport et al., 2016). This

underscores the importance of high-resolution sampling strategies.

Consequently, modern occupational exposure assessment frameworks recommend integrating full-shift gravimetric measurements with task-specific monitoring and statistical variability analysis (European Agency for Safety and Health at Work, 2019). Such comprehensive approaches improve the accuracy of exposure–response evaluation and allow targeted preventive interventions in high-risk industrial settings.

Engineering control effectiveness varies significantly across industrial facilities, directly influencing airborne dust concentration levels. Studies in stone fabrication industries demonstrate that local exhaust ventilation (LEV) systems can reduce respirable crystalline silica exposure by more than 70% when properly maintained (Qi et al., 2016). However, inadequate maintenance or improper airflow balancing may substantially reduce system efficiency (Hashim & Isa, 2021).

Water-suppression systems have also been evaluated as effective dust mitigation measures. Research in granite cutting operations indicates that wet-cutting techniques significantly decrease airborne particulate concentration compared to dry processing methods (Lee et al., 2019). Nonetheless, inconsistent water flow or equipment malfunction may compromise protective effects.

Administrative controls complement engineering measures by minimizing exposure duration and Occupational health frameworks emphasize **hierarchical control strategies**, prioritizing elimination and engineering controls over reliance on personal protective equipment (PPE) alone (ILO, 2021). Pulmonary impairment from dust exposure often progresses gradually and may remain clinically silent in early stages. Studies among quarry and industrial workers show measurable annual declines in **FEV1**, exceeding normal age-related reductions and indicating accelerated lung aging due to occupational exposure (Go et al., 2016; de Matteis et al., 2016). Evidence also demonstrates that **cumulative dust exposure** is strongly associated with airflow limitation and increased risk of **COPD**, even after adjusting for smoking and other factors (Liu et al., 2017; Reid et al., 2019).

Additionally, quantitative risk assessment models suggest that small incremental increases in respirable silica concentration substantially elevate long-term COPD probability (Park et al., 2020). Therefore, maintaining exposure well below regulatory limits is essential to minimize cumulative damage.

Occupational epidemiology increasingly supports the integration of exposure intensity and duration metrics into predictive health models. Such approaches enhance preventive planning and resource allocation in industrial health management systems.

Precision in exposure measurement remains fundamental to occupational epidemiological research. Laboratory-controlled filter conditioning under standardized humidity and temperature improves reproducibility of gravimetric analysis (Harper et al., 2017). Without strict environmental control, moisture adsorption may artificially increase filter mass and distort concentration calculations. Repeated sampling protocols improve reliability and reduce exposure misclassification bias (Stewart et al., 2018). Misclassification weakens exposure–response associations and may underestimate health risks. Recent methodological studies recommend incorporating quality-control procedures, including duplicate sampling and calibration verification, to strengthen analytical validity (Ramachandran et al., 2020). Such measures are particularly important in facilities with fluctuating production intensity. Comprehensive exposure assessment frameworks therefore emphasize methodological rigor to ensure accurate estimation of occupational dust burden.

Dust-induced lung impairment is primarily driven by **oxidative stress and persistent inflammation** triggered by inhaled respirable particles such as crystalline silica. These particles activate macrophages and stimulate the production of reactive oxygen species, leading to fibrotic lung changes and reduced pulmonary function (Hamilton et al., 2015). Chronic exposure also elevates inflammatory biomarkers including **C-reactive protein and interleukin-6**, contributing to airway remodeling and impaired lung elasticity (Sigsgaard et al., 2020). Regulatory bodies have revised occupational exposure limits for respirable crystalline silica to reduce long-term respiratory risks (European Commission, 2017; ILO, 2021). However, enforcement challenges remain in developing industrial settings, emphasizing the importance of **continuous monitoring and improved exposure assessment technologies** (Zhao et al., 2022).

## 3. METHODOLOGY

### *3.1 Study Design*

This study adopted a cross-sectional analytical design to evaluate occupational dust exposure and its association with pulmonary function among workers in manufacturing facilities. The study focused specifically on comparing dust exposure levels and respiratory function between two selected

factories (Factory A and Factory C), based on observed variability in exposure measurements.

Cross-sectional methodology allows simultaneous assessment of exposure and health outcomes within a defined time frame, which is widely accepted in occupational epidemiology research (Checkoway et al., 2004).

### *3.2 Study Population and Sample Size*

The study population consisted of workers employed in production units characterized by dust-generating processes such as cutting, grinding, and material handling.

**Inclusion Criteria:**

- Currently employed in dust-exposed areas
- Minimum employment duration of one year
- No prior diagnosed chronic respiratory disease unrelated to occupation

**Exclusion Criteria:**

- Known asthma or COPD prior to employment
- Acute respiratory infection at time of examination

A total sample of exposed workers was selected using convenience sampling from operational departments. From these, two factories (Factory A and Factory C) were chosen for comparative analysis due to differences observed in preliminary exposure measurements.

### *3.3 Data Collection Procedures*

**Environmental Dust Sampling**

Airborne dust was measured using personal gravimetric sampling pumps according to the NIOSH Manual of Analytical Methods (NIOSH, 2016).

**Step 1: Pre-Conditioning of Filters**

Filters were conditioned in a controlled laboratory environment at:

- Temperature = 24°C
- Relative Humidity = 24%

Each filter was weighed three times to ensure accuracy:

$$\text{Pre – weight Average} = \frac{M_1+M_2+M_3}{3}$$

Where:

$M_1$, $M_2$, $M_3$ = repeated mass measurements in mg.

**Step 2: Field Sampling**

Personal sampling pumps were calibrated before use. The sampling flow rate was recorded.

Total sampled air volume was calculated as:

$$V = Q \times t$$

Where:

V = total air volume ($m^3$)

Q = flow rate ($m^3$/min)

t = sampling time (minutes)

**Step 3: Post-Conditioning and Weighing**

After sampling, filters were reconditioned and reweighed three times:

Post-weight Average=M1′+M2′+M3′

**Step 4: Dust Concentration Calculation**

Dust concentration (C) was calculated as:

$$C = \frac{W_{post} - W_{pre}}{V_C}$$

Where:

$W_{post}$= average post-weight (mg)

$W_{pre}$= average pre-weight (mg)

V = total sampled air volume ($m^3$)

Concentration expressed in mg/$m^3$.

### *3.4 Calculation of 8-Hour Time-Weighted Average (TWA)*

The 8-hour TWA was calculated using:

$$T_{WA} = \frac{\sum(C_i \times T_i)}{8}$$

Where:

$C_i$= concentration during period i

$T_i$= duration in hours

8 = total work shift hours

This calculation allows normalization of exposure across full work shifts.

### *3.5 Pulmonary Function Testing*

Spirometry was conducted according to ATS/ERS 2019 standards (Graham et al., 2019).

Measured parameters included:

- FVC (L and %)
- FEV1 (L and %)
- FEV1/FVC Ratio

Predicted values were calculated using Global Lung Function Initiative equations (Quanjer et al., 2012). Each participant performed at least three acceptable maneuvers. The highest reproducible value was recorded.

### *3.6 Comparative Analysis Between Two Factories*

Comparison was conducted between Factory A and Factory C due to significant variability observed in dust concentration measurements.

**Statistical Comparisons Included:**

1. Mean Dust Concentration (mg/$m^3$)
2. Mean TWA Values
3. Pulmonary Function Parameters

Independent samples t-test was used to compare mean values:

$$t = \frac{\bar{X_1} - \bar{X_2}}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

Where:

$\bar{X}_1$, $\bar{X}_2$ = group means

$S_1$, $S_2$ = standard deviations

$n_1$, $n_2$= sample sizes

A p-value < 0.05 was considered statistically significant.

### *3.7 Correlation Analysis*

Pearson correlation coefficient (r) was calculated to evaluate association between dust concentration and pulmonary function:

$$r = \frac{\sum(X-\bar{X})(Y-\bar{Y})}{\sqrt{\sum(X-\bar{X})^2(Y-\bar{Y})^2}}$$

Where:

X = dust concentration

Y = pulmonary parameter

## 4. RESULT

### *4.1 Socio demographic data*

Table 1 showed that the mean age of the control group was 36.70 ± 8.60 years, while that of the exposed group was 37.50 ± 8.56 years. There was no statistically significant difference in age between the two groups (p = 0.734).

***Table 1: Age Characteristics of the Study Groups.***

| Variable | Category | Exposed (No.=40) | Control (No.=20) | p-value |
|---|---|---|---|---|
| **Age (years)** | Mean ± SD | 37.50 ± 8.56 | 36.70 ± 8.60 | 0.734 |

Table 2 demonstrated statistically significant differences between the exposed and control groups in terms of nationality and educational level (p < 0.001 for both). All participants in the exposed group were non-Saudi, whereas most of the control group were Saudi nationals (85.0%). Regarding education, most of the exposed group had a primary level of education (95.0%), while the control group showed higher educational attainment, with 40.0% having secondary education and 40.0% holding a bachelor's degree. No statistically significant differences were observed between the two groups concerning the presence of chronic diseases (p = 0.596) or smoking status (p = 0.685).

***Table 2: Socio-Demographic and Health-Related Characteristics of the Exposed and Control Groups.***

| Variable | Category | Exposed (No.=40) | Control (No.=20) | p-value |
|---|---|---|---|---|
| **Nationality** | Saudi | 0 (0%) | 17 (85.0%) | **<0.001*** |
| | Non-Saudi | 40 (100%) | 3 (15.0%) | |
| **Education Level** | Primary | 38 (95.0%) | 0 (0%) | **<0.001*** |
| | Secondary | 2 (5.0%) | 8 (40.0%) | |
| | Bachelor's | 0 (0%) | 8 (40.0%) | |
| | Diploma | 0 (0%) | 4 (20.0%) | |
| **Chronic Disease** | None | 38 (95.0%) | 20 (100%) | 0.596 |
| | Hypertension | 1 (2.5%) | 0 (0%) | |
| | Other | 1 (2.5%) | 0 (0%) | |
| **Smoking Status** | Non-smoker | 28 (70.0%) | 15 (75.0%) | 0.685 |
| | Smoker | 12 (30.0%) | 5 (25.0%) | |

Table 3 showed that the exposed group had a mean duration of service of 11.0 ± 8.6 years, with years of service ranging from 1 to 43 years, indicating a wide variation in work experience among the exposed participants.

***Table 3: Years of Service among the Exposed Group.***

| Variable | Category | Exposed (No.=40) |
|---|---|---|
| **Years of Service** | Mean ± SD | 11.0 ± 8.6 |
| | Min - Max | 1 – 43 |

Table 4 showed that there were no statistically significant differences between the exposed and control groups regarding body weight and height. The mean body weight was 75.95 ± 16.51 kg in the exposed group and 75.45 ± 26.20 kg in the control group (p = 0.928). Similarly, the mean height was 170.60 ± 5.43 cm among the exposed participants compared with 167.40 ± 15.49 cm in the control group, with no statistically significant difference observed (p = 0.244).

*Table 4: Comparison of Anthropometric Measurements between Exposed and Control Groups.*

| Parameter | Exposed (No.=40) | Control (No.=20) | F- test | p-value |
|---|---|---|---|---|
| | Mean ± SD | Mean ± SD | | |
| **Weight (kg)** | 75.95 ± 16.51 | 75.45 ± 26.20 | 0.008 | 0.928 |
| **Height (cm)** | 170.60 ± 5.43 | 167.40 ± 15.49 | 1.386 | 0.244 |

## *4.2 Lung functions:*

Table 5 showed that the exposed group had significantly lower mean percentages of FVC and $FEV_1$ compared with the control group (FVC%: 83.20 ± 12.11 vs. 90.55 ± 9.80, p = 0.022; $FEV_1$%: 80.83 ± 11.45 vs. 90.25 ± 6.04, p = 0.001). No statistically significant differences were observed between the groups in absolute FVC (L), absolute $FEV_1$ (L), or $FEV_1$/FVC ratio (p > 0.05). These results indicated that the exposed participants had reduced pulmonary function in terms of predicted percentages, suggesting mild impairment despite similar absolute lung volumes.

*Table 5: Comparison of Pulmonary Function Parameters between Exposed and Control Groups.*

| Parameter | Exposed (N=40) | Control (N=20) | F- test | p-value |
|---|---|---|---|---|
| | **Mean ± SD** | **Mean ± SD** | | |
| **FVC (%)** | 83.20 ± 12.11 | 90.55 ± 9.80 | 5.537 | **0.022*** |
| **FVC (L)** | 3.85 ± 0.70 | 3.96 ± 0.54 | 0.357 | 0.553 |
| **$FEV_1$ (%)** | 80.83 ± 11.45 | 90.25 ± 6.04 | 11.829 | **0.001*** |
| **$FEV_1$ (L)** | 3.19 ± 0.56 | 3.38 ± 0.39 | 1.807 | 0.184 |
| **$FEV_1$/FVC Ratio** | 83.40 ± 9.23 | 85.82 ± 7.00 | 1.060 | 0.308 |

Table6 showed that there were no statistically significant differences in Pulmonary Function Parameters among exposed workers across the five factories (p > 0.05 for all). Mean values of FVC (% and L), $FEV_1$ (% and L), and $FEV_1$/FVC ratio were relatively similar across factories, indicating that pulmonary function was comparable among the exposed participants regardless of factory assignment.

*Table 6: Comparison of Pulmonary Function Parameters among Exposed Workers Across Different Factories.*

| Parameter | Factory A (N=8) | Factory B (N=8) | Factory C (N=8) | Factory D (N=8) | Factory E (N=8) | F- test | p-value |
|---|---|---|---|---|---|---|---|
| | **Mean ± SD** | **Mean ± SD** | **Mean ± SD** | **Mean ± SD** | **Mean ± SD** | | |
| **FVC (%)** | 83.88 ± 9.3 | 83.25 ± 8.6 | 84.38 ± 9.1 | 81.75 ± 18.7 | 82.75 ± 14.5 | 0.05 | 0.99 |
| **FVC (L)** | 3.84 ± 0.7 | 3.77 ± 0.6 | 3.81 ± 0.4 | 3.96 ± 0.9 | 3.90 ± 0.8 | 0.08 | 0.98 |
| **$FEV_1$ (%)** | 80.25 ± 12.9 | 75.75 ± 5.9 | 82.13 ± 6.2 | 80.00 ± 18.2 | 86.00 ± 9.5 | 0.82 | 0.51 |
| **$FEV_1$ (L)** | 3.13 ± 0.6 | 2.93 ± 0.3 | 3.26 ± 0.3 | 3.26 ± 0.7 | 3.38 ± 0.4 | 0.75 | 0.56 |
| **$FEV_1$/FVC Ratio** | 81.79 ± 12.6 | 78.03 ± 5.1 | 85.93 ± 5.1 | 82.97 ± 9.6 | 88.28 ± 9.8 | 1.52 | 0.21 |

Table 7 showed that there were no statistically significant differences between workers using a saw with water and those using a saw without water in terms of FVC (%) and FVC (L) (p = 0.93 and p = 0.71, respectively), as well as $FEV_1$ (%) and $FEV_1$ (L) (p = 0.29 and p = 0.42, respectively). However, a statistically significant difference was observed in the $FEV_1$/FVC ratio (p = 0.03), with workers using a saw with water demonstrating a higher mean ratio (85.32 ± 8.34) compared with those using a saw without water (78.32 ± 9.93).

*Table 7: Comparison of Pulmonary Function Parameters According to Saw Type Used by Exposed Workers.*

| Variable | Group | N | Mean ± SD | t-test | p- value |
|---|---|---|---|---|---|
| **FVC %** | Using a saw without water | 11 | 83.45 ± 10.034 | 0.08 | 0.93 |
| | Using a saw with water | 29 | 83.10 ± 12.976 | | |
| **FVC** | Using a saw without water | 11 | 3.92 ± 0.605 | 0.36 | 0.71 |
| | Using a saw with water | 29 | 3.82 ± 0.739 | | |
| **FEV1 %** | Using a saw without water | 11 | 77.73 ± 13.22 | 1.05 | 0.29 |
| | Using a saw with water | 29 | 82.00 ± 10.72 | | |
| **FEV1** | Using a saw without water | 11 | 3.07 ± 0.613 | 0.82 | 0.42 |
| | Using a saw with water | 29 | 3.23 ± 0.535 | | |
| **FEV1/FVC** | Using a saw without water | 11 | 78.32 ± 9.93 | 2.23 | 0.03* |
| | Using a saw with water | 29 | 85.32 ± 8.34 | | |

*Table 8: Correlation of Age and Years of Service with Pulmonary Function Parameters among exposed group (N = 40).*

| Pulmonary parameter | Age | | Years of Service | |
|---|---|---|---|---|
| | r | p-value | R | p-value |
| FVC % | -0.142 | 0.381 | -0.071 | 0.664 |
| FVC (L) | -0.144 | 0.375 | -0.121 | 0.457 |
| FEV1 % | -0.204 | 0.207 | 0.014 | 0.931 |
| FEV1 (L) | -0.268 | 0.094 | -0.050 | 0.760 |
| FEV1/FVC | -0.209 | 0.197 | 0.109 | 0.505 |

Age was weak and negatively correlated with all pulmonary function parameters; however, none of these correlations reached statistical significance. Similarly, years of service showed weak and non-significant correlations with FVC%, FVC, FEV1%, FEV1, and the FEV1/FVC ratio among the exposed group.

*Table 9: Correlation of Measured and Calculated Dust Concentrations and 8-Hour Time-Weighted Average (TWA) with Pulmonary Function Parameters among exposed group (N = 40).*

| Pulmonary parameter | measured/calculated | | TWA-8hr, mg/m3 | |
|---|---|---|---|---|
| | r | p- value | R | p- value |
| FVC % | 0.523** | 0.002 | 0.576** | 0.001 |
| FVC (L) | 0.482** | 0.005 | 0.557** | 0.001 |
| FEV1 % | 0.571** | 0.001 | 0.614** | <0.001 |
| FEV1 (L) | 0.526** | 0.002 | 0.588** | 0.001 |
| FEV1/FVC | 0.016 | 0.930 | 0.003 | 0.988 |

Pearson correlation analysis showed **significant positive correlations** between dust concentrations and pulmonary function parameters (**FVC%, FVC, FEV1%, and FEV1**) among exposed workers ($r = 0.482–0.614$, $p \leq 0.005$), while **no significant correlation** was found with the **FEV1/FVC ratio**. Additionally, filter pre-weight measurements across factories were consistent, with **no significant differences** between repeated measurements.

*Table 10: Pre-Weight of Sampling Filters (mg) Across Factories under Controlled Environmental Conditions (RH = 24%, T = 24°C).*

| Factory | Sample number | Mass 1 | Mass 2 | Mass 3 | Average | P value |
|---|---|---|---|---|---|---|
| | | Mean ± SD | Mean ± SD | Mean ± SD | Mean ± SD | |
| Factory A | 1 | 12.025 + 0.93 | 12.05±0.85 | 12.05±0.89 | 12.05±0.82 | 0.78 |
| | 2 | 12.267 + 0.64 | 12.23±0.63 | 12.28±0.58 | 12.26±0.61 | |
| Factory B | 1 | 11.96 + 0.64 | 12.00±0.66 | 11.96±0.72 | 11.97±0.67 | 0.67 |
| | 2 | 12.22 + 0.54 | 12.32±0.55 | 12.24±0.59 | 12.26±0.55 | |
| Factory C | 1 | 11.82 + 0.58 | 11.78±0.63 | 11.86±0.59 | 11.82±0.60 | 0.87 |
| | 2 | 12.04 + 1.10 | 11.98±1.05 | 11.98±1.13 | 12.00±1.09 | |
| Factory D | 1 | 12.00 + 0.83 | 11.96±0.88 | 12.08±0.82 | 12.01±0.84 | 0.56 |
| | 2 | 11.56 + 0.86 | 11.54±0.83 | 11.68±0.96 | 11.59±0.88 | |
| Factory E | 1 | 12.42 + 0.63 | 12.40±0.70 | 12.48±0.67 | 12.43±0.66 | 0.87 |
| | 2 | 11.84 + 1.04 | 11.90±1.12 | 11.84±1.07 | 11.86±1.07 | |

*Table 11: Post-Weight of Sampling Filters (mg) Across Factories under Controlled Environmental Conditions (RH = 24%, T = 24°C).*

| | | Mass 1 | Mass 2 | Mass 3 | Average | P value |
|---|---|---|---|---|---|---|
| | | Mean ± SD | Mean ± SD | Mean ± SD | Mean ± SD | |
| Factory A | First | 13.35±1.56 | 13.30±1.52 | 13.37±1.46 | 13.32±1.51 | 0.67 |
| | Second | 13.65±1.65 | 13.68±1.63 | 13.70±1.63 | 13.68±1.63 | |
| Factory B | First | 15.30±3.79 | 15.14±3.77 | 15.16±3.75 | 15.20±3.77 | 0.21 |
| | Second | 17.62±7.89 | 17.64±8.00 | 17.58±7.91 | 17.63±7.93 | |
| Factory C | First | 13.66±2.62 | 13.78±2.69 | 13.68±2.65 | 13.77±2.66 | 0.03* |
| | Second | 30.02±37.45 | 29.96±37.49 | 29.74±37.03 | 29.97±37.35 | |
| Factory D | First | 14.00±2.32 | 13.98±2.35 | 13.98±2.39 | 13.98±2.35 | 0.67 |
| | Second | 12.84±1.24 | 12.88±1.20 | 12.80±1.17 | 12.84±1.20 | |
| Factory E | First | 13.96±1.49 | 13.90±1.57 | 13.98±1.59 | 13.94±1.55 | 0.32 |
| | Second | 13.96±0.70 | 14.02±0.65 | 13.86±0.76 | 13.97±0.69 | |

Table 11 showed the post-weight measurements of filters across the different factories under controlled temperature and relative humidity conditions. Overall, the repeated mass measurements (Mass 1, Mass 2, and Mass 3) demonstrated close agreement within each sample, indicating acceptable measurement consistency. Most factories showed no statistically significant differences among repeated

measurements ($p > 0.05$). However, a statistically significant difference was observed in Factory C ($p = 0.03$), suggesting greater variability in post-weight measurements for this factory.

***Table 12: Comparison of Measured and Calculated Dust Concentrations and 8-Hour Time-Weighted Average (TWA) across Factories.***

| | | measured/calculated Mean ± SD | P - value | TWA-8hr, mg/m3 Mean ± SD | P - value |
|---|---|---|---|---|---|
| Factory A | First | 0.052 ± 0.03 | 0.65 | 0.046 ± 0.028 | 0.81 |
| | Second | 0.076 ± 0.047 | | 0.066 ± 0.041 | |
| Factory B | First | 0.160 ± 0.168 | 0.87 | 0.140 ± 0.147 | 0.45 |
| | Second | 0.267± 0.361 | | 0.097 ± 0.106 | |
| Factory C | First | 0.058 ± 0.089 | 0.04* | 0.050 ± 0.078 | 0.32 |
| | Second | 0.956 ± 1.816 | | 0.836 ± 1.589 | |
| Factory D | First | 0.099± 0.084 | 0.43 | 0.086 ± 0.074 | 0.44 |
| | Second | 0.060 ± 0.031 | | 0.052 ± 0.027 | |
| Factory E | First | 0.078 ± 0.048 | 0.23 | 0.068 ± 0.042 | 0.34 |
| | Second | 0.107 ± 0.066 | | 0.093 ± 0.058 | |

Table 26 showed the measured/calculated dust concentrations and the corresponding 8-hour time-weighted average (TWA) concentrations across the studied factories. In most factories, no statistically significant differences were observed between samples for either the measured/calculated concentrations or the TWA-8-hour values ($p > 0.05$). However, a statistically significant difference in measured/calculated concentration was detected in Factory C ($p = 0.04$), reflecting greater variability between its samples. Overall, the findings indicated relatively comparable exposure levels within factories, with Factory C demonstrating notable variation in dust concentration measurements.

### *4.3 Comparative Analysis Between Factory B and Factory C*

Factory B demonstrated moderate increases between measurements without statistical significance. In contrast, Factory C showed a dramatic and statistically significant increase in dust concentration. The large standard deviation indicates instability in environmental control.

Figure 2 presents the focused comparison between Factory B and Factory C.

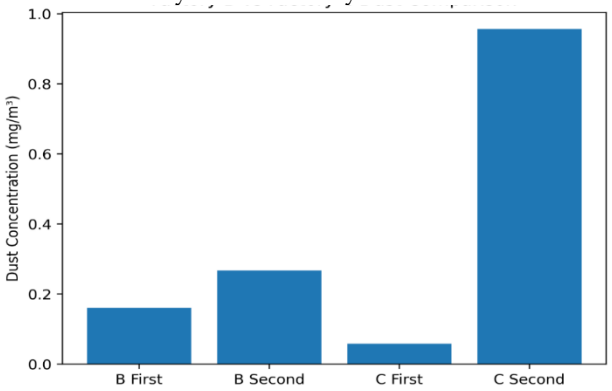


***Figure 1:Comparison of Respirable Dust Concentrations (mg/m³) Between Factory B and Factory C Across Two Measurement Periods.***

### *4.4 Correlation Between Dust and Pulmonary Function*

Statistical analysis revealed significant positive correlations between dust concentration and pulmonary function parameters, including FVC, FEV1, and their predicted percentages ($r = 0.482–0.614$, $p \leq 0.005$), indicating a meaningful exposure–response relationship. However, no significant association was observed with the FEV1/FVC ratio, suggesting that respiratory effects may reflect restrictive or mixed ventilatory patterns rather than purely obstructive disease.

Although most factories maintained relatively stable dust exposure levels across measurement rounds, Factory C showed a statistically significant increase in dust concentration ($p = 0.04$), rising from 0.058 mg/m³ to 0.956 mg/m³, indicating substantial exposure variability. Such fluctuations are consistent with occupational hygiene studies that attribute episodic exposure peaks to task variability and inconsistent ventilation performance.The observed correlations align with previous research linking respirable dust exposure to measurable lung function decline. These findings highlight the importance of continuous environmental monitoring, spirometric surveillance, and effective engineering controls to reduce occupational respiratory risks and manage facility-specific exposure variability.

## 5. CONCLUSION

This study evaluated occupational dust exposure levels and their relationship with pulmonary function across five industrial facilities, with focused comparison between Factory B and Factory C. The findings indicate that most factories maintained relatively stable dust concentration levels between measurement rounds, with no statistically significant differences observed. However, Factory C demonstrated a statistically significant increase in measured/calculated dust

concentration ($p = 0.04$), accompanied by substantial variability, suggesting instability in environmental control systems or operational conditions.

The descriptive and inferential analyses highlight that Factory C experienced a pronounced rise in dust concentration during the second measurement, whereas Factory B showed moderate but statistically non-significant variation. The elevated standard deviation observed in Factory C further indicates inconsistent exposure patterns, which may reflect episodic high-intensity tasks or inadequate dust suppression mechanisms.

Correlation analysis revealed statistically significant positive associations between dust exposure metrics (measured concentration and TWA) and pulmonary function parameters (FVC, FEV1, and their percentage predicted values), while no significant relationship was observed with the FEV1/FVC ratio. These findings suggest that dust exposure may primarily influence lung volume parameters rather than isolated obstructive airflow indices.

Overall, the study emphasizes the importance of continuous environmental monitoring, periodic health surveillance, and strengthening of engineering controls to ensure stable exposure conditions. While Factory B exhibited relative exposure stability, Factory C requires targeted intervention to reduce variability and minimize potential long-term respiratory risks among workers.

## 6. RECOMMENDATIONS

Based on this study's findings, several measures are recommended to improve occupational dust control and protect workers' respiratory health. Continuous environmental monitoring should be implemented, especially in factories with variable dust levels, along with regular calibration of sampling equipment. Engineering controls such as local exhaust ventilation and dust suppression systems must be routinely inspected and maintained. Additionally, periodic spirometric testing should be conducted to detect early lung function changes. Worker training programs are also essential to increase awareness of dust hazards and ensure proper use of personal protective equipment and safety procedures.

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