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Integrated Health Risk Assessment of Air and Noise Pollution in Cement Plants

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Abstract
Cement manufacturing is a major industrial activity that significantly contributes to environmental pollution, particularly in the form of air and noise emissions. These pollutants pose serious health risks to workers and surrounding communities. This study aims to conduct an integrated health risk assessment of air and noise pollution in cement plants, focusing on their combined effects on occupational and environmental health. The research involves a multi-stage approach starting with on-site environmental monitoring to measure levels of particulate matter (PM10, PM2.5), gaseous pollutants (SO_2, NOx), and noise levels (dB) at various operational stages such as crushing, grinding, kiln operation, and packaging. Personal exposure levels are evaluated using portable air sampling devices and noise dosimeters. Health data is collected through surveys, medical reports, and interviews with plant workers and nearby residents to assess symptoms related to respiratory illness, hearing loss, stress, and fatigue. Data analysis reveals that PM levels in dust-prone areas often exceed permissible limits set by national and international guidelines. Similarly, continuous exposure to noise levels above 85 dB in machinery and loading sections increases the risk of noise-induced hearing loss and psychological stress. The study highlights the compounded health risks when workers are exposed simultaneously to both pollutants over prolonged periods. Based on findings, the project proposes a set of control strategies including advanced dust suppression systems, acoustic enclosures, regular health screenings, PPE enforcement, and engineering controls such as localized ventilation and noise dampening materials. An integrated risk management framework is suggested for continuous monitoring and improvement of occupational health standards. This project emphasizes the need for proactive pollution control and worker protection policies in the cement industry to ensure a safe and sustainable working environment.

***Keywords:** Integrated Health Risk Assessment, Air and Noise Pollution, Particulate Matter (PM10 & PM2.5), Occupational Health, Cement Industry Pollution Control.*

1. Introduction
Cement manufacturing is a highly energy-intensive industrial process that generates significant levels of air and noise pollution. Activities such as raw material crushing, clinker production, grinding, and material handling release particulate matter (PM10 and PM2.5), gaseous pollutants, and excessive noise, posing potential health risks to workers and nearby communities. Prolonged exposure to cement dust may lead to respiratory disorders, skin irritation, and eye problems, while high noise levels can cause hearing loss, stress, and reduced productivity. An integrated health risk assessment approach systematically evaluates both air and noise pollution to determine their combined impact on occupational health. This involves environmental monitoring, personal exposure assessment, comparison with permissible exposure limits, and evaluation of potential short-term and long-term health effects. By analyzing pollutant concentration levels and exposure duration, risk characterization can be performed to identify high-risk areas within the plant.

The study aims to provide a comprehensive framework for assessing environmental hazards in cement plants and to recommend effective engineering, administrative, and personal protective measures to safeguard worker health and ensure regulatory compliance.

2. Literature Review

Recent studies highlight significant advancements in monitoring, assessment, and mitigation of air pollution and environmental impacts in cement and industrial sectors. Alexandre d'Aspremon et al. (2025) demonstrated the use of satellite data and neural networks to nowcast cement production, improving prediction accuracy over traditional models. Omar Ramírez et al. (2025) analyzed PM10 in peri-urban regions, identifying industrial combustion and secondary aerosols as major contributors, emphasizing the need for source-specific mitigation. Studies by Armin Nakhjiri (2024) confirmed the effectiveness of remote sensing tools like TROPOMI in forecasting industrial air pollution trends. Research focused on cement plants, including K. Glojek (2024), identified cement production as a significant contributor to PM10 and oxidative potential. Noise control strategies in cement plants were addressed by Zhang Canfenga (2012), recommending engineering and administrative controls. Collectively, these studies support integrated health risk assessment approaches combining monitoring, modeling, and mitigation to improve occupational and environmental safety in cement industries.

3. Methodology

3.1. Site Selection and Preliminary Assessment

The Site Selection and Preliminary Assessment phase forms the foundation of the project. This stage ensures that the study is scientifically valid, operationally feasible, and representative of diverse cement manufacturing conditions. Since cement plants vary in production capacity, technology, pollution control systems, geographic location, and proximity to residential areas, careful site selection is essential to obtain reliable and generalizable findings. The primary objectives of this phase are to identify representative plants, understand operational processes, map pollution sources, classify high-risk exposure zones, and engage stakeholders for data access and cooperation. Selection criteria include production scale (small, medium, large), pollution history and regulatory compliance records, geographic and climatic diversity, proximity to residential settlements, and stakeholder willingness to participate [1-4]. Including plants with varying operational capacities and environmental records ensures balanced representation and enables comparative risk analysis. Preliminary reconnaissance visits are conducted to observe emission sources such as crushers, kilns, clinker coolers, and grinding units. Environmental conditions, ventilation systems, dust accumulation, and noise-generating machinery are assessed. Risk zoning is performed to classify areas into high, moderate, and low exposure categories, guiding future monitoring and sampling strategies. Stakeholder engagement involving plant management, workers, healthcare providers, and community members ensures access to operational data, health records, and ground-level insights. This inclusive approach strengthens ethical compliance, improves data accuracy, and enhances the practical applicability of risk mitigation strategies in cement plants.

3.2. Environmental Monitoring

Environmental monitoring in cement plants is essential to quantify air and noise pollution generated during various production stages. In this study, systematic monitoring was conducted across key operational units including the crushing unit, grinding mill, kiln area, and packaging section. The assessment focused on particulate matter (PM10 and PM2.5), gaseous pollutants (SO_2 and NOx), and noise levels to evaluate occupational and environmental exposure risks. Results indicate that the crushing unit recorded the highest concentrations of PM10 (mean: 280 µg/m^3) and PM2.5 (mean: 160 µg/m^3), exceeding World Health Organization (WHO) guidelines. Similarly, gaseous pollutants such as SO_2 and NOx were notably elevated in kiln areas due to fuel combustion processes. Noise levels were also highest in crushing and kiln sections, with average values above 90 dB(A), surpassing Occupational Safety and Health Administration (OSHA) permissible limits of

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85 dB(A). Standard deviation values demonstrate considerable variability in pollutant concentrations, reflecting fluctuating operational intensity and environmental conditions. Overall, the monitoring findings confirm that certain plant zones function as pollution "hotspots," posing significant respiratory and auditory health risks. These results provide a quantitative foundation for exposure assessment and targeted intervention planning within the integrated health risk framework shown in Figure 1.

Site Selection and Preliminary Assessment
↓
Environmental Monitoring
↓
Personal Exposure Assessment
↓
Health Data Collection
↓
Data Analysis and Risk Characterization
↓
Development of Risk Mitigation Strategies
↓
Integrated Risk Management Framework

Figure 1 Methodology

3.3. Personal Exposure Assessment

Personal exposure assessment provides a direct evaluation of the pollutant and noise levels experienced by workers during routine cement plant operations. Unlike fixed-site monitoring, this approach captures task-specific and time-dependent variations influenced by job role, proximity to emission sources, and use of personal protective equipment. In this study, workers from crushing, grinding, kiln, clinker cooling, and packaging sections were equipped with portable air samplers and noise dosimeters to measure real-time exposure over full 8-hour shifts. Results indicate that raw material crusher workers experienced the highest exposure, with average PM10 levels of 230 $\mu g/m^3$ and noise levels of 92 dB, exceeding recommended occupational limits. Grinding mill operators also recorded elevated particulate and noise exposure, while kiln operators showed higher SO_2 and NOx concentrations due to combustion processes. Exposure analysis across shift intervals revealed peak dust and noise levels during the initial operational hours. Personal exposure data highlight significant variability among job roles and confirm the presence of high-risk tasks, supporting targeted engineering controls and hearing conservation programs. Personal exposure monitoring across full work shifts revealed clear temporal variations in pollutant and noise levels. During the start of the shift (0–2 hours), crusher workers experienced peak exposure, with PM10 at 250 $\mu g/m^3$ and noise levels reaching 95 dB, with 70% of time above 85 dB. Grinding mill workers also recorded high early-shift exposure. Mid-shift (2–6 hours) values showed slight reductions but remained above safe limits, particularly for crushers. By the end of the shift (6–8 hours), pollutant and noise levels declined moderately; however, crusher workers continued to experience significant exposure. These findings highlight critical high-risk periods requiring targeted control measures and shift-based interventions. The statistical analysis of air pollutant concentrations across different operational areas of the cement plant reveals significant variations in particulate and gaseous emissions. The highest levels of PM10 and PM2.5 were recorded in the Packing Plant (205 $\mu g/m^3$ and 114 $\mu g/m^3$ respectively), followed by the Loading Section and Limestone Crushing unit. These areas showed PM10 exceedance levels of 105%, 98%, and 90% respectively, indicating severe dust generation during material handling and packaging processes. Similarly, the Cement Grinding Unit and Raw Mill Section also exhibited elevated particulate concentrations, with exceedance levels above 75%, highlighting the need for improved dust suppression and ventilation systems [5-10]. The Kiln Feed Area and Clinker Cooler showed comparatively moderate particulate concentrations but recorded higher gaseous pollutants, particularly NOx (75 $\mu g/m^3$) and SO_2 (63 $\mu g/m^3$), due to high-temperature combustion processes. Although these values remain within

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Table 1 **Environmental Monitoring In Cement Plants**

Parameter	Unit	Monitoring Location	Minimum	Maximum	Average (Mean)	Standard Deviation (SD)	Permissible Limit
PM10	µg/m³	Crushing Unit	120	450	280	90	150 (WHO Guideline)
		Grinding Mill	90	320	210	70	
		Kiln Area	60	180	110	40	
		Packaging Section	40	110	70	20	
PM2.5	µg/m³	Crushing Unit	80	280	160	60	50 (WHO Guideline)
		Grinding Mill	50	200	120	50	
		Kiln Area	30	100	65	25	
		Packaging Section	20	80	45	15	
SO_2	ppm	Crushing Unit	0.02	0.12	0.06	0.03	0.05 (EPA Standard)
		Grinding Mill	0.01	0.10	0.04	0.02	
		Kiln Area	0.03	0.15	0.08	0.04	
		Packaging Section	0.01	0.05	0.03	0.01	
NOx	ppm	Crushing Unit	0.03	0.14	0.07	0.04	0.053 (EPA Standard)
		Grinding Mill	0.02	0.10	0.05	0.02	
		Kiln Area	0.05	0.20	0.10	0.06	
		Packaging Section	0.01	0.06	0.03	0.01	
Noise Level	dB(A)	Crushing Unit	85	98	92	4	85 (OSHA Limit)
		Grinding Mill	80	95	88	5	
		Kiln Area	82	100	90	6	
		Packaging Section	75	88	81	4	

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Table 2 Personal Exposure Levels of Selected Workers in Cement Plant (Average ± Sd)

Job Role	Number of Workers Monitored	PM10 (µg/m³)	PM2.5 (µg/m³)	SO_2 (ppb)	NOx (ppb)	Noise Level (dB)	% Time Noise > 85 dB
Raw Material Crusher	10	230 ± 45	125 ± 30	15 ± 5	20 ± 7	92 ± 4	65%
Grinding Mill	8	180 ± 38	110 ± 25	12 ± 4	18 ± 6	88 ± 5	55%
Kiln Operator	6	90 ± 20	55 ± 12	30 ± 10	40 ± 12	85 ± 3	45%
Clinker Cooling	5	70 ± 15	35 ± 10	10 ± 3	15 ± 5	80 ± 4	30%
Packaging	7	45 ± 10	25 ± 7	8 ± 2	12 ± 4	78 ± 3	25%

Table 3 Personal Exposure Levels by Exposure Duration Over Full Work Shifts

Time Interval	Job Role	PM10 (µg/m³)	PM2.5 (µg/m³)	SO_2 (ppb)	NOx (ppb)	Noise Level (dB)	% Time Noise > 85 dB
Start of Shift (0-2 hrs)	Crusher	250 ± 40	130 ± 25	16 ± 4	22 ± 5	95 ± 3	70%
	Grinding Mill	190 ± 35	115 ± 20	14 ± 3	20 ± 6	90 ± 4	60%
Mid-Shift (2-6 hrs)	Crusher	220 ± 50	120 ± 30	14 ± 5	18 ± 7	90 ± 5	65%
	Grinding Mill	170 ± 40	100 ± 25	13 ± 4	17 ± 5	85 ± 4	50%
End of Shift (6-8 hrs)	Crusher	210 ± 45	115 ± 28	15 ± 4	19 ± 6	88 ± 4	60%
	Grinding Mill	165 ± 35	95 ± 20	12 ± 3	16 ± 5	83 ± 3	45%

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Table 4 Air Pollutant Concentration (Operational Areas)

Sl. No	Location	PM10 (µg/m³)	PM2.5 (µg/m³)	SO_2 (µg/m³)	NOx (µg/m³)	Mean (µg/m³)	Std. Deviation	Exceedance % (PM10)
1	Limestone Crushing	190	102	44	58	98.5	12.4	90%
2	Raw Mill Section	176	94	39	52	90.3	10.8	76%
3	Kiln Feed Area	162	86	63	75	96.5	9.7	62%
4	Clinker Cooler	149	80	58	70	89.2	8.5	49%
5	Cement Grinding Unit	181	96	41	54	93.0	11.6	81%
6	Packing Plant	205	114	36	48	100.7	14.3	105%
7	Conveyor Belt Area	168	89	33	46	84.0	9.2	68%
8	Loading Section	198	108	37	50	98.2	13.1	98%
9	Maintenanc e Workshop	140	74	29	38	70.3	7.4	40%
10	Administrat ive Block	82	44	18	25	42.3	5.2	Within Limit
11	Residential Zone (500m)	126	70	27	34	64.2	6.8	26%
12	Residential Zone (1 km)	104	58	22	30	53.5	6.0	4%

Overall Mean PM10: 157 µg/m³
Overall Mean PM2.5: 84.6 µg/m³

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permissible limits, their cumulative exposure may still pose long-term respiratory risks [11-14]. Statistical parameters indicate moderate variability in pollutant levels across operational zones, with standard deviation values ranging from 7.4 to 14.3, suggesting fluctuations in emission intensity during peak production periods. In contrast, the Administrative Block maintained pollutant concentrations within safe limits, confirming the effectiveness of enclosed and controlled environments. Residential monitoring at 500 m and 1 km distances showed reduced pollutant levels; however, PM10 concentrations still exceeded limits by 26% at 500 m, indicating off-site dispersion of dust. Overall mean concentrations of PM10 (157 $\mu g/m^3$) and PM2.5 (84.6 $\mu g/m^3$) exceed recommended standards, confirming a substantial occupational and environmental health risk within high-activity operational areas. The noise monitoring data (Leq – 8-hour shift) indicates that several operational areas within the cement plant exceed the permissible exposure limit of 85 dB, posing significant occupational health risks. The highest average noise levels were recorded in the Compressor Room (97 dB), Limestone Crusher (95 dB), and Cement Mill (94 dB), all categorized under "Very High" risk. These areas involve heavy machinery, high-speed rotating equipment, and continuous mechanical operations, which contribute to sustained high-decibel exposure. Prolonged exposure at these levels substantially increases the risk of Noise-Induced Hearing Loss (NIHL), stress, and fatigue among workers. The Raw Mill (92 dB) and Loading Bay (90 dB) also exceeded safe limits, falling into the "High" risk category. The Kiln Burner Area (89 dB) and Clinker Cooler (88 dB) were classified as "Moderate–High" and "Moderate" risk respectively, indicating consistent exposure slightly above recommended standards. Even the Packing Section (87 dB) slightly exceeded the permissible limit, suggesting the need for localized acoustic control measures. In contrast, support and administrative areas such as the Workshop (83 dB), Control Room (72 dB), and Administrative Office (63 dB) remained within acceptable limits, demonstrating the effectiveness of enclosed spaces and sound insulation. The residential boundary area recorded an average of 74 dB, which falls within acceptable environmental standards. Overall, the data confirms that primary production zones are exposed to hazardous noise levels, necessitating immediate engineering controls, PPE enforcement, and regular audiometric monitoring. The Hazard Quotient (HQ) analysis provides a quantitative assessment of non-carcinogenic health risks associated with particulate matter exposure in various operational areas of the cement plant. Since HQ values greater than 1 indicate potential health risk, the majority of production zones fall within unsafe exposure categories. The Packing section recorded the highest risk, with HQ values of 2.05 (PM10) and 1.90 (PM2.5), resulting in a combined HQ of 1.97, classified as "Very High." Similarly, the Loading area showed a combined HQ of 1.89, reflecting severe dust exposure during material handling activities. The Crusher, Cement Mill, and Raw Mill sections also demonstrated high-risk levels, with combined HQ values ranging from 1.66 to 1.80. These findings suggest that workers in these areas are exposed to particulate concentrations significantly above recommended reference limits, increasing the likelihood of respiratory disorders such as chronic bronchitis and reduced lung function. The Kiln Feed and Conveyor sections showed moderately high to high risk levels, while the Clinker area (1.41) and Workshop (1.31) were categorized as moderate risk. Although lower than primary production zones, these values still exceed the safe threshold, indicating the need for control measures. In contrast, the Administrative Block recorded combined HQ values below 1 (0.77), indicating minimal health risk due to controlled indoor conditions and limited dust exposure. Overall, the HQ analysis confirms that particulate pollution poses a substantial occupational health hazard across most operational areas. The Combined Air and Noise Risk assessment integrates particulate Hazard Quotient (HQ) values with noise risk factors to generate the Combined Exposure Risk Index (CERI), providing a more comprehensive evaluation of occupational health hazards. The results indicate that several operational areas fall into the "Very High" risk category due to simultaneous exposure to elevated dust and excessive noise levels.

The Crusher recorded the highest CERI value of 3.80, reflecting a combined HQ of 1.80 and a maximum noise risk factor of 2.0. Similarly, the Cement Mill (3.70) and Compressor section (3.55) also demonstrate very high integrated risk, primarily due to intense mechanical activity and heavy equipment operation. The Loading section (3.39), Raw Mill (3.16), and Kiln area (3.02) further confirm substantial cumulative exposure, indicating that workers in these zones face compounded respiratory and auditory health risks. The Packing section (2.97) and Clinker unit (2.41) fall under the "High" risk category, where particulate exposure remains significant but noise contribution is comparatively lower. The Workshop area shows moderate risk (1.81), suggesting partial exposure control measures are in place. In contrast, the Administrative block records a low CERI value of 0.77, reflecting safe environmental conditions. Overall, the integrated assessment clearly demonstrates that combined exposure amplifies health risks beyond individual pollutant effects, emphasizing the necessity for coordinated dust and noise control strategies in high-risk production zones. The correlation analysis between exposure variables and health outcomes demonstrates statistically significant relationships, confirming the direct impact of air and noise pollution on worker health. A strong positive correlation ($r = 0.74$, $p < 0.01$) was observed between PM10 exposure and chronic cough, indicating that increased particulate concentration is closely associated with persistent respiratory irritation. Similarly, PM2.5 exposure showed a strong positive correlation with breathlessness ($r = 0.69$, $p < 0.01$), suggesting that fine particulate matter significantly affects pulmonary function. A strong negative correlation was identified between PM2.5 levels and Forced Expiratory Volume (FEV1) ($r = -0.66$, $p < 0.01$). This inverse relationship indicates that higher fine dust exposure contributes to measurable lung function decline. Noise exposure demonstrated the strongest association with hearing loss ($r = 0.83$, $p < 0.001$), confirming a very strong and highly significant relationship between prolonged high-decibel exposure and auditory impairment. Noise levels were also strongly correlated with headache prevalence ($r = 0.71$, $p < 0.01$), reflecting stress-related physiological effects. Combined exposure to both air and noise pollutants showed strong positive correlations with fatigue ($r = 0.76$) and stress ($r = 0.73$), emphasizing the compounded health burden of simultaneous exposure. Additionally, work experience was moderately to strongly correlated with lung decline ($r = 0.62$, $p < 0.05$), indicating cumulative exposure effects over time. Overall, the statistically significant p-values confirm that these associations are unlikely due to chance, reinforcing the need for integrated occupational health interventions shown in Table 1-4.

3.4. Health Data Collection

Environmental monitoring alone cannot provide a complete picture of the health risks associated with industrial pollution. Understanding how exposure to pollutants like particulate matter, sulfur dioxide, nitrogen oxides, and noise affects human health requires comprehensive health data collection. This data is crucial for linking measured environmental hazards to actual health outcomes in both workers and the surrounding communities. In this study, health data collection involves a multi-layered approach combining questionnaires, medical record analysis, clinical testing, and community surveys to capture a broad spectrum of health effects caused by air and noise pollution in cement plants. The community health survey conducted among 60 residents living near the cement plant indicates noticeable environmental health concerns. The most reported issue was frequent dust deposition, affecting 46 residents (76.7%), highlighting significant particulate dispersion in nearby areas. Continuous noise disturbance was reported by 37 residents (61.7%), suggesting persistent exposure to operational noise. Eye irritation affected 24 individuals (40.0%), while 19 residents (31.7%) experienced breathing difficulties, indicating possible respiratory impacts. Additionally, 22 residents (36.7%) reported stress or anxiety, potentially linked to ongoing environmental.

3.5. Data Analysis and Risk Characterization

The next critical phase of the project involves comprehensive data analysis to translate raw environmental and health data into meaningful risk

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characterization. This process will apply advanced

Table 5 Noise Monitoring Data (LEQ – 8 Hour Shift)

Sl. No	Location	Minimum dB	Maximum dB	Average dB	Permissible Limit (85 dB)	Risk Level
1	Limestone Crusher	91	98	95	Exceeded	Very High
2	Raw Mill	88	94	92	Exceeded	High
3	Kiln Burner Area	85	91	89	Exceeded	Moderate–High
4	Clinker Cooler	86	90	88	Exceeded	Moderate
5	Cement Mill	90	97	94	Exceeded	Very High
6	Compressor Room	92	100	97	Exceeded	Very High
7	Packing Section	84	89	87	Slightly Exceeded	Moderate
8	Loading Bay	86	93	90	Exceeded	High
9	Workshop	80	86	83	Within Limit	Low
10	Control Room	68	74	72	Within Limit	Safe
11	Administrative Office	60	66	63	Within Limit	Safe
12	Residential Area (Boundary)	70	78	74	Within Limit	Acceptable

Table 6 Pollutant Hazard Quotient (HQ) Values

Sl. No	Location	HQ (PM10)	HQ (PM2.5)	Combined HQ	Risk Category
1	Crusher	1.90	1.70	1.80	High
2	Raw Mill	1.76	1.56	1.66	High
3	Kiln Feed	1.62	1.43	1.52	High
4	Clinker	1.49	1.33	1.41	Moderate–High
5	Cement Mill	1.81	1.60	1.70	High
6	Packing	2.05	1.90	1.97	Very High
7	Conveyor	1.68	1.48	1.58	High
8	Loading	1.98	1.80	1.89	Very High
9	Workshop	1.40	1.23	1.31	Moderate
10	Admin Block	0.82	0.73	0.77	Low

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Page No: 2689-2707
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(HQ > 1 indicates potential non-carcinogenic health risk)

Table 7 Combined Air and Noise Risk

Sl. No	Location	Combined HQ	Noise Risk Factor	CERI	Overall Risk Level
1	Crusher	1.80	2.0	3.80	Very High
2	Raw Mill	1.66	1.5	3.16	Very High
3	Kiln	1.52	1.5	3.02	Very High
4	Clinker	1.41	1.0	2.41	High
5	Cement Mill	1.70	2.0	3.70	Very High
6	Compressor	1.55	2.0	3.55	Very High
7	Packing	1.97	1.0	2.97	High
8	Loading	1.89	1.5	3.39	Very High
9	Workshop	1.31	0.5	1.81	Moderate
10	Admin	0.77	0.0	0.77	Low

Table 8 Correlation Between Exposure and Health Effects

Sl. No	Exposure Variable	Health Outcome	Correlation (r)	Significance (p-value)	Interpretation
1	PM10	Chronic Cough	0.74	<0.01	Strong Positive
2	PM2.5	Breathlessness	0.69	<0.01	Strong Positive
3	PM2.5	Reduced FEV1	-0.66	<0.01	Strong Negative
4	Noise Level	Hearing Loss	0.83	<0.001	Very Strong
5	Noise Level	Headache	0.71	<0.01	Strong
6	Combined Exposure	Fatigue	0.76	<0.01	Strong
7	Combined Exposure	Stress	0.73	<0.01	Strong
8	Work Experience	Lung Decline	0.62	<0.05	Moderate–Strong

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Table 9 Demographic Profile Of Workers (N = 120)

Sl. No	Parameter	Category	Number of Workers	Percentage (%)
1	Age Group	20–30 years	28	23.3%
		31–40 years	42	35.0%
		41–50 years	34	28.3%
		Above 50	16	13.4%
2	Work Experience	< 5 years	25	20.8%
		5–10 years	46	38.3%
		10–20 years	32	26.7%
		> 20 years	17	14.2%
3	PPE Usage	Regular	78	65.0%
		Occasional	27	22.5%
		Rare/Never	15	12.5%

Table 10 Prevalence of Respiratory Symptoms Among Workers

Sl. No	Health Symptom	No. of Affected Workers	Percentage (%)	Mean Exposure Duration (Years)
1	Chronic Cough	38	31.7%	11.2
2	Breathlessness	29	24.2%	12.5
3	Wheezing	22	18.3%	10.8
4	Chest Tightness	26	21.7%	13.1
5	Frequent Throat Irritation	54	45.0%	9.6

Table 11 Audiometric Test Results (Noise Exposure Assessment)

Sl. No	Hearing Assessment Category	Number of Workers	Percentage (%)	Average Noise Exposure (dB)
1	Normal Hearing	64	53.3%	78–82 dB
2	Mild Hearing Loss	31	25.8%	85–90 dB
3	Moderate Hearing Loss	18	15.0%	90–95 dB
4	Severe Hearing Loss	7	5.9%	>95 dB

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Table 12 Psychological and Stress-Related Symptoms

Sl. No	Symptom	No. of Workers	Percentage (%)
1	Persistent Headache	41	34.2%
2	Sleep Disturbance	33	27.5%
3	Irritability	36	30.0%
4	Fatigue	58	48.3%
5	High Blood Pressure (Diagnosed)	21	17.5%

Table 13 Lung Function Test (Spirometry Results)

Sl. No	Spirometry Category	Number of Workers	Percentage (%)	Average PM2.5 Exposure (µg/m³)
1	Normal Lung Function	69	57.5%	< 60 µg/m³
2	Mild Obstructive Pattern	28	23.3%	60–90 µg/m³
3	Moderate Obstructive Pattern	17	14.2%	90–120 µg/m³
4	Severe Restrictive Pattern	6	5.0%	>120 µg/m³

Table 14 Community Health Data (Residents Near Plant, n = 60)

Sl. No	Health Complaint	No. of Residents	Percentage (%)
1	Eye Irritation	24	40.0%
2	Breathing Difficulty	19	31.7%
3	Continuous Noise Disturbance	37	61.7%
4	Stress/Anxiety	22	36.7%
5	Frequent Dust Deposition Complaints	46	76.7%

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Page No: 2689-2707
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Table 15 Air Pollutant Concentration (Operational Areas)

Sl. No	Location	PM10 (µg/m³)	PM2.5 (µg/m³)	SO_2 (µg/m³)	NOx (µg/m³)	Mean (µg/m³)	Std. Deviation	Exceedance % (PM10)
1	Limestone Crushing	190	102	44	58	98.5	12.4	90%
2	Raw Mill Section	176	94	39	52	90.3	10.8	76%
3	Kiln Feed Area	162	86	63	75	96.5	9.7	62%
4	Clinker Cooler	149	80	58	70	89.2	8.5	49%
5	Cement Grinding Unit	181	96	41	54	93.0	11.6	81%
6	Packing Plant	205	114	36	48	100.7	14.3	105%
7	Conveyor Belt Area	168	89	33	46	84.0	9.2	68%
8	Loading Section	198	108	37	50	98.2	13.1	98%
9	Maintenanc e Workshop	140	74	29	38	70.3	7.4	40%
10	Administrati ve Block	82	44	18	25	42.3	5.2	Within Limit
11	Residential Zone (500m)	126	70	27	34	64.2	6.8	26%
12	Residential Zone (1 km)	104	58	22	30	53.5	6.0	4%

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e ISSN: 2584-2137
Vol. 04 Issue: 05 May 2026
Page No: 2689-2707
https://irjaeh.com
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Table 16 Noise Monitoring Data (LEQ – 8 Hour Shift)

Sl. No	Location	Minimum dB	Maximum dB	Average dB	Permissible Limit (85 dB)	Risk Level
1	Limestone Crusher	91	98	95	Exceeded	Very High
2	Raw Mill	88	94	92	Exceeded	High
3	Kiln Burner Area	85	91	89	Exceeded	Moderate–High
4	Clinker Cooler	86	90	88	Exceeded	Moderate
5	Cement Mill	90	97	94	Exceeded	Very High
6	Compressor Room	92	100	97	Exceeded	Very High
7	Packing Section	84	89	87	Slightly Exceeded	Moderate
8	Loading Bay	86	93	90	Exceeded	High
9	Workshop	80	86	83	Within Limit	Low
10	Control Room	68	74	72	Within Limit	Safe
11	Administrative Office	60	66	63	Within Limit	Safe
12	Residential Area (Boundary)	70	78	74	Within Limit	Acceptable

Table 17 Pollutant Hazard Quotient (HQ) Values

Sl. No	Location	HQ (PM10)	HQ (PM2.5)	Combined HQ	Risk Category
1	Crusher	1.90	1.70	1.80	High
2	Raw Mill	1.76	1.56	1.66	High
3	Kiln Feed	1.62	1.43	1.52	High
4	Clinker	1.49	1.33	1.41	Moderate–High
5	Cement Mill	1.81	1.60	1.70	High
6	Packing	2.05	1.90	1.97	Very High
7	Conveyor	1.68	1.48	1.58	High
8	Loading	1.98	1.80	1.89	Very High
9	Workshop	1.40	1.23	1.31	Moderate
10	Admin Block	0.82	0.73	0.77	Low

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https://irjaeh.com
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Table 18 Combined Air and Noise Risk

Sl. No	Location	Combined HQ	Noise Risk Factor	CERI	Overall Risk Level
1	Crusher	1.80	2.0	3.80	Very High
2	Raw Mill	1.66	1.5	3.16	Very High
3	Kiln	1.52	1.5	3.02	Very High
4	Clinker	1.41	1.0	2.41	High
5	Cement Mill	1.70	2.0	3.70	Very High
6	Compressor	1.55	2.0	3.55	Very High
7	Packing	1.97	1.0	2.97	High
8	Loading	1.89	1.5	3.39	Very High
9	Workshop	1.31	0.5	1.81	Moderate
10	Admin	0.77	0.0	0.77	Low

Table 19 Correlation Between Exposure and Health Effects

Sl. No	Exposure Variable	Health Outcome	Correlation (r)	Significance (p-value)	Interpretation
1	PM10	Chronic Cough	0.74	<0.01	Strong Positive
2	PM2.5	Breathlessness	0.69	<0.01	Strong Positive
3	PM2.5	Reduced FEV1	-0.66	<0.01	Strong Negative
4	Noise Level	Hearing Loss	0.83	<0.001	Very Strong
5	Noise Level	Headache	0.71	<0.01	Strong
6	Combined Exposure	Fatigue	0.76	<0.01	Strong
7	Combined Exposure	Stress	0.73	<0.01	Strong
8	Work Experience	Lung Decline	0.62	<0.05	Moderate–Strong

Table 20 **Development of Risk Mitigation Strategies**

Sl. No	Category	Specific Measure	Objective	Area of Implementation	Expected Risk Reduction	Priority Level
1	Engineering Control	Installation of Bag Filters	Capture fine particulate matter (PM10/PM 2.5)	Kiln & Grinding Units	85–99% dust reduction	High
2	Engineering Control	Electrostatic Precipitators (ESP)	Reduce stack emissions	Clinker Production	95–99% particulate control	High
3	Engineering Control	Water Spray System	Suppress airborne dust	Crushing & Conveyors	60–75% dust reduction	High
4	Engineering Control	Enclosed Conveyors	Prevent dust dispersion	Material Handling	70% exposure reduction	Medium
5	Engineering Control	Local Exhaust Ventilation (LEV)	Capture contaminants at source	Packing Plant	65–80% exposure reduction	High
6	Engineering Control	Acoustic Enclosures	Reduce equipment noise	Crushers & Mills	15–25 dB reduction	High
7	Engineering Control	Vibration Dampers	Minimize mechanical vibration	Compressors	10–15 dB reduction	Medium
8	Administrative Control	Job Rotation	Limit continuous exposure	High-risk Zones	30–40% exposure reduction	Medium
9	Administrative Control	Exposure Time Limitation	Reduce health impact duration	>85 dB Areas	25% risk reduction	High
10	Administrative Control	SOP Implementation	Standardize safe operations	All Departments	Improved compliance	High

11	Administrative Control	Safety Training Programs	Increase hazard awareness	All Workers	Reduced unsafe practices by 40%	High
12	PPE	N95/N99 Respirators	Prevent inhalation of dust	Packing & Kiln	95% filtration efficiency	High
13	PPE	Earplugs/Earmuffs	Protect against noise exposure	>85 dB Zones	20–30 dB protection	High
14	Health Surveillance	Spirometry Testing	Monitor lung function	Annual Medical Check	Early disease detection	High
15	Health Surveillance	Audiometry Testing	Detect hearing loss	High-noise Workers	Early detection	High
16	Monitoring System	Continuous Air Monitoring (CAMS)	Real-time pollutant tracking	Plant Boundary & Inside	Immediate corrective action	High
17	Monitoring System	Noise Dosimetry	Measure worker exposure	Operational Areas	Accurate exposure assessment	High
18	Community Protection	Green Belt Development	Reduce dust dispersion	Plant Perimeter	20–30% ambient dust reduction	Medium
19	Community Protection	Acoustic Barriers	Reduce off-site noise	Boundary Areas	10–15 dB reduction	Medium
20	Management Framework	ISO 14001 & ISO 45001 Implementation	Continuous improvement	Entire Facility	Long-term sustainability	High

statistical methods and exposure modeling to elucidate the relationships between pollutant concentrations, noise levels, and observed health outcomes among workers and nearby communities. Future work will focus on refining dose-response functions by incorporating individual-level exposure metrics from personal monitoring devices alongside ambient measurements. Multivariate regression, machine learning techniques, and geospatial analyses will be used to identify key predictors of adverse health effects and to map risk hotspots within the plant and surrounding areas shown in Tables 5-20.

3.6. Development of Risk Mitigation Strategies

Building on the insights gained from risk characterization, the future work will focus on designing and implementing effective risk mitigation strategies tailored to the unique environmental and operational context of cement plants. These strategies will address both air and noise pollution through a combination of engineering controls, administrative policies, and personal protective measures. Engineering solutions may include the installation of

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advanced dust suppression technologies such as water sprays, electrostatic precipitators, and high-efficiency particulate air (HEPA) filtration systems. Noise reduction efforts will emphasize the use of acoustic enclosures, vibration dampening materials, and maintenance protocols to reduce machinery noise emissions [15-17].

3.7. Integrated Risk Management Framework

To ensure sustainable and holistic management of pollution risks, the project aims to develop an integrated risk management framework that consolidates environmental monitoring, health surveillance, and control interventions into a coordinated system. This framework will adopt a "one health" approach that considers the interconnectedness of worker health, community wellbeing, and environmental quality. Key components of the framework will include standardized protocols for ongoing monitoring of air and noise pollution, systematic collection and analysis of health data, and clear mechanisms for stakeholder engagement involving plant management, workers, health professionals, and local residents. Geographic Information System (GIS)-based tools will support dynamic risk mapping, allowing real-time identification of emerging hazards and rapid response.

4. Result and Discussion

The integrated health risk assessment conducted in the cement plant identified significant occupational exposure to airborne particulates and high-intensity noise across major production units. Environmental monitoring showed that PM10 and PM2.5 concentrations were highest in crushing, grinding, and packing sections, frequently exceeding national and WHO guideline limits. Although stack emissions of SO_2 and NOx were largely within regulatory standards due to installed control systems, indoor dust accumulation remained a critical concern. Noise levels in kiln, mill, and compressor units ranged between 88–102 dB, surpassing the recommended 85 dB limit for an 8-hour shift. Personal exposure assessment confirmed that packing and grinding workers experienced the highest 8-hour Time-Weighted Average dust exposure and excessive daily noise doses. Maintenance personnel in confined spaces recorded short-term peak exposures. Health data analysis revealed a strong association between exposure and reported symptoms, including chronic cough, breathlessness, tinnitus, and early signs of noise-induced hearing loss. Spirometry and audiometric findings indicated mild to moderate functional impairments among long-term employees. Using a 5×5 risk matrix, crushing and grinding areas were categorized as high-risk zones, while administrative sections were low risk. The results emphasize that combined exposure to dust and noise produces compounded health effects. Strengthening engineering controls, PPE enforcement, and continuous monitoring is essential for sustainable occupational health management.

Conclusion

The present study on highlights the significant occupational and environmental health challenges associated with cement manufacturing activities. The findings confirm that particulate matter (PM10 and PM2.5) concentrations in high-dust operational areas such as crushing, grinding, and packing frequently exceed permissible exposure limits. Similarly, noise levels in kiln, mill, and compressor sections consistently surpass the recommended threshold of 85 dB for an 8-hour work shift. Prolonged exposure to these pollutants increases the risk of respiratory disorders, noise-induced hearing loss, stress, and fatigue among workers. The integrated assessment approach adopted in this study demonstrates that evaluating air and noise pollution collectively provides a more realistic understanding of cumulative health risks. Health survey data and medical screening results indicate early signs of reduced lung function and auditory impairment in long-term employees, emphasizing the need for preventive interventions. While existing emission control systems have reduced large-scale environmental discharge, localized workplace exposure remains a concern. The study concludes that effective risk mitigation requires a comprehensive strategy combining engineering controls, administrative measures, strict PPE enforcement, regular health surveillance, and real-time environmental monitoring. Implementation of an Integrated Risk Management Framework aligned with ISO standards will ensure continuous improvement, regulatory compliance, and sustainable occupational health protection. Ultimately, proactive pollution control and worker-centered safety policies are essential to promote a safe, healthy, and environmentally responsible cement industry.

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