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Comprehensive Impact Assessment of Dust Emissions from Benghazi Cement Plant: Health Burden, Environmental Degradation, and Mitigation Efficacy

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ABSTRACT

Dust emissions from cement plants pose a significant threat to public health and the environment, particularly in semi-urban areas where industrial activities interface with residential and agricultural zones. This study aims to conduct a comprehensive quantitative assessment of pollution from the Benghazi Cement Plant and its multi-faceted impacts. A three-year longitudinal study (2022-2024) was conducted in the industrial and semi-urban Al-Hawari area of Benghazi, Libya. Particulate Matter (PM10 and PM2.5) concentrations were measured in workplace and ambient areas using high-precision monitors (DustTrak II, Grimm). Soil samples were collected for pH and agricultural productivity analysis. Health data were obtained from official records. Statistical analyses (ANOVA, Pearson correlation, linear regression) were employed for data analysis. The results showed that chronic air pollution levels were notably high, with mean concentrations of PM10 (102 ± 26.10 µg/m³) and PM2.5 (63.6 ± 2.5 µg/m³) exceeding WHO guideline limits by more than double (92%–164%) and showing no significant improvement over the study years ($P > 0.05$). A clear seasonal variation was observed, with peak concentrations recorded during spring and summer due to the influence of Ghibli winds, and the differences between seasons were statistically significant ($P = 0.003$). Regression analysis revealed a strong relationship ($R^2 = 0.85$) between PM2.5 levels and respiratory disease cases, indicating that each 1 µg/m³ increase in PM2.5 corresponded to approximately five additional cases. The findings also indicated marked environmental degradation, with soil pH decreasing by 7.6%–8.2% and agricultural productivity declining by 11.3%–12.5%. Although minor improvements were observed in mitigation measures, they remained insufficient to control the critical levels of pollution.

Keywords: Cement pollution, Particulate Matter, PM2.5, PM10, Occupational Exposure, Benghazi.

التقييم الشامل لتأثيرات الانبعاثات الغبارية من مصنع بنغازي للإسمنت: العبء الصحي، التدهور البيئي، وفعالية استراتيجيات التخفيف

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ملخـــــــص البحــــــث

انبعاثات الغبار من مصانع الأسمنت تُكل تهديدًا كبيرا للصحة العامة وللبيئة، خصوصًا في المناطق شبه الحضرية التي تتداخل فيها الأنشطة الصناعية مع المناطق السكنية والزراعية. تهدف هذه الدراسة إلى إجراء تقييم كمي شامل للتلوث الناتج عن مصنع أسمنت بنغازي وآثاره المتعددة الجوانب. تم تنفيذ دراسة طولية على مدى ثلاث سنوات (2022–2024) في منطقة الهواري الصناعية وشبه الحضرية بمدينة بنغازي، ليبيا. جرى قياس تركيز الجسيمات العالقة (**PM10**) و (**PM2.5**)في أماكن العمل والمناطق المحيطة باستخدام أجهزة عالية الدقة (**DustTrak II**)، (**Grimm**). كما تم جمع عينات من التربة لتحليل درجة الحموضة (**pH**) والإنتاجية الزراعية، وتم الحصول على البيانات الصحية من السجلات الرسمية. أُستخدمت التحليلات الإحصائية (**ANOVA**، ارتباط بيرسون، والانحدار الخطي) لمعالجة البيانات. أظهرت النتائج أن مستويات تلوث الهواء المزمن كانت مرتفعة بشكل ملحوظ، حيث بلغ متوسط تركيز **PM10** نحو (102 ميكروغرام/م³) و**PM2.5** نحو (63.6 ميكروغرام/م³)، متجاوزةً الحدود الإرشادية لمنظمة الصحة العالمية بأكثر من الضعف (بنسبة تتراوح بين 92%–164%)، دون تحسن يُذكر خلال سنوات الدراسة ($P > 0.05$).كما لوحظ تباين موسمي واضح، حيث سجلت أعلى التركيزات خلال فصلي الربيع والصيف نتيجة تأثير رياح القبلي، وكانت الفروقات بين الفصول ذات دلالة إحصائية ($P = 0.003$) وكشف تحليل الانحدار عن علاقة قوية ($R^2 = 0.85$)بين مستويات **PM2.5** وحالات أمراض الجهاز التنفسي، مما يشير إلى أن كل زيادة بمقدار 1 ميكروغرام/م³ في تركيز **PM2.5** تقابلها تقريبًا خمس حالات إضافية من الأمراض التنفسية. كما بينت النتائج وجود تدهور بيئي واضح، حيث انخفضت قيمة **pH** في التربة بنسبة تتراوح بين 7.6%–8.2%، وتراجعت الإنتاجية الزراعية بنسبة 11.3%–12.5%. وعلى الرغم من وجود بعض التحسينات الطفيفة في إجراءات التخفيف من التلوث، إلا أنها ظلت غير كافية للسيطرة على المستويات الحرجة للتلوث.

الكلمات المفتاحية: تلوث الإسمنت، الجسيمات الدقيقة، **PM2.5**، **PM10**، التعرض المهني، بنغازي.

1. INTRODUCTION

The cement industry is a cornerstone of the global construction sector. However, it is also classified as one of the most energy-intensive and polluting industries. Dust emissions, particularly particulate matter (PM) with diameters less than 10 micrometers (PM10) and less than 2.5 micrometers (PM2.5), rank among the most significant pollutants due to their detrimental effects on human health and ecosystem integrity. These fine particles can penetrate deep into the respiratory system, causing chronic diseases such as asthma, bronchitis, cardiovascular ailments, and impacting cognitive development in children.

Environmentally, the deposition of cement dust, rich in alkaline compounds like calcium oxide (CaO), disrupts the soil's chemical balance, increasing its alkalinity (pH), which impairs nutrient absorption and degrades soil fertility and agricultural productivity in the long term. This problem is exacerbated in arid and semi-arid regions, where geological and climatic factors, such as sparse vegetation cover and seasonal dust-laden winds (e.g., the "Ghibli" winds in Libya), increase the rates of emission and long-range transport of these particles. Globally, numerous studies, such as those by Al-Tamimi et al. (2020) in Saudi Arabia and Iraq and Mokhtar et al. (2021) in Egypt, have recorded significant exceedances of PM10 and PM2.5 concentrations near cement plants, linked to adverse health and environmental outcomes. Despite this global evidence, a significant research gap persists in Libya, where studies lack longitudinal duration, in-depth seasonal analysis, and quantitative linkage between pollution levels and field-based health and environmental outcomes. The Benghazi Cement Plant, located in the Al-Hawari district in close proximity to dense residential neighborhoods and agricultural zones, presents a stark case study of this issue.

Therefore, this study aimed to bridge this gap by conducting continuous and comprehensive monitoring over a three-year period (2022-2024). It quantified the actual pollution levels in the workplace and surrounding environment, analyzed seasonal variations in detail, and measured the tangible impacts on community health (through recorded data on respiratory illnesses) and the environment (through analyzing soil degradation and agricultural productivity). The study also provided a critical evaluation of the effectiveness of the plant's current mitigation measures. The obtained results, which demonstrated massive and persistent exceedances of safety limits, a strong correlation between dust and diseases, and clear soil degradation, reinforce the scientific argument regarding the severe risk of this pollution. Consequently, this study not only provides an accurate diagnosis of the problem but also offers an evidence-based foundation for developing targeted and effective mitigation strategies, thereby contributing to the impetus for stricter environmental and industrial policies in Libya and the region.

2. STUDY OBJECTIVES

1. Assess Air and Soil Pollution Levels: Quantify the seasonal and annual concentrations of particulate matter (PM10 and PM2.5) and their impacts on soil properties (pH) and agricultural productivity around the plant.

2. Analyze Health and Environmental Burden: Correlate dust exposure levels with recorded rates of respiratory illnesses in the local community and evaluate the extent of environmental degradation.

3. Evaluate Current Mitigation Strategies: Gauge the effectiveness of implemented dust control measures (mechanical, environmental, and personal) and propose sustainable improvements.

3. MATERIALS AND METHODS

3.1 Study Area and Temporal Framework

This study was conducted in the Al-Hawari industrial district, southeast of Benghazi, Libya, where the Benghazi Cement Plant is located (Approximate coordinates: 20.114°E, 32.015°N). The area was selected for its semi-urban context, interspersed with residential clusters and agricultural lands, allowing for the assessment of both occupational and ambient exposure. The study covered a longitudinal period from January 2022 to December 2024.

3.2 Sampling Design:

Spatial Coverage: Twenty fixed monitoring points were established within a 5-km radius of the plant, distributed across the four cardinal directions (North, South, East, West). Points included locations at distances of 0 m (on-site), 500 m, 1000 m, 2500 m, and 5000 m from the plant.

Temporal Frequency: Air and soil samples were collected bi-monthly, totaling 18 sampling rounds per year, to ensure representation of seasonal variations.

3.3 Air Quality Monitoring and Particulate Analysis:

Instrumentation:

- DustTrak II Aerosol Monitor (TSI 8530) for real-time PM10 and PM2.5 readings.
- Grimm Portable Aerosol Spectrometer (Model 11-D) for particle size distribution and gravimetric comparison.
- High-Volume Air Sampler (HVAS) for collecting Total Suspended Particulates (TSP) for laboratory analysis.

Protocol: Each air monitoring session lasted 24 hours. Instruments were calibrated prior to each deployment. Filters from HVAS and Grimm were analyzed gravimetrically in a controlled laboratory (temperature and humidity) to determine mass concentration.

Quality Assurance: Duplicate sampling was performed at 10% of sites per round, blank filter controls were used for each set, and cross-validation between monitors was conducted.

3.4 Soil Sampling and Laboratory Analysis:

Sample Collection: Soil samples were collected from depths of 0-10 cm, 10-20 cm, and 20-30 cm at each monitoring site using a stainless-steel auger. Composite samples were formed from 3 sub-samples per site.

Laboratory Analysis: Soil pH was measured using a calibrated pH meter in a 1:2.5 soil-water slurry. On selected samples, elemental analysis for major and heavy metals was performed using X-ray Fluorescence (XRF) to identify cement-related accumulation (e.g., Calcium).

3.5 Health Data Collection:

Aggregated and anonymized data on respiratory and allergic conditions (e.g., asthma, bronchitis) were collected from official records at the Benghazi Municipal Health Department and local hospitals and clinics surrounding the plant during the study period.

3.6 Data Processing and Statistical Analysis:

All data were processed and analyzed using SPSS (Statistical Package for the Social Sciences) version 26 and Microsoft Excel.

Descriptive Statistics: Calculation of arithmetic mean, standard deviation (±SD), and range

Inferential Statistics:

One-Way Analysis of Variance (ANOVA): To compare mean particulate concentrations between different years (2022, 2023, 2024) and between the four seasons to assess annual and seasonal variation.

Independent Samples T-test: To compare agricultural yield data and soil properties before and after dust deposition (using historical baseline data for comparison).

Pearson Correlation Coefficient (r): To analyze the strength and direction of the linear relationship between:

- PM10 and PM2.5 concentrations.
- PM2.5 concentrations and the number of reported respiratory illness cases.

Simple Linear Regression Analysis: To initially model the quantitative relationship between PM2.5 concentration (independent variable) and the number of respiratory cases (dependent variable).

Multiple Linear Regression: To estimate the net effect of PM2.5 on respiratory cases after controlling for potential confounding meteorological variables. The model included PM2.5, mean temperature, and relative humidity as independent variables. Regression parameters are reported with 95% confidence intervals (CI).

Significance Level: A p-value of less than 0.05 was considered statistically significant.

3.7 Evaluation of Mitigation Measures:

A semi-quantitative scoring matrix (on a 1–10 scale) was developed based on direct field observations, interviews with plant management, and document reviews. Five key categories were evaluated: mechanical filtration efficiency, water spraying implementation, green buffer establishment and maintenance, Personal Protective Equipment (PPE) compliance, and environmental monitoring infrastructure efficacy. Score trends over the years were then analyzed using time-series regression analysis.

4. RESULTS

4.1 Dust Concentration Levels:

Mean PM10 (102 µg/m³) and PM2.5 (63.6 µg/m³) consistently exceeded WHO guidelines. ANOVA ($p > 0.05$) showed no statistically significant difference between annual means, indicating persistent pollution.

4.2 Seasonal Variation:

ANOVA ($p = 0.003$) indicated statistically significant seasonal differences, with the highest levels in summer (PM10: 130.3 µg/m³) and spring (PM10: 116.3 µg/m³). The correlation between PM10 and PM2.5 was very strong ($r = 0.98$).

***4.3 Health and Environmental Impact**:* Regression analysis showed a strong linear relationship between PM2.5 and respiratory cases ($R^2 = 0.87$). Soil pH and agricultural yield decreased significantly ($p < 0.05$).

4.4 Mitigation Measures Effectiveness:

The evaluation showed gradual improvement in scores from 2022 to 2024, but they remained insufficient to control pollution effectively.

Statistical and Descriptive Analysis:

Overall Arithmetic Mean (2022–2024):

- PM10 = 102 ± 6.1 µg/m³(95% CI: 98.5 - 105.5)
- PM2.5 = 63.6 ± 2.5 µg/m³(95% CI: 61.8 - 65.4)

Table1. Airborne Particulate Concentration Levels**.**

Year	Annual Mean PM10 (µg/m³)	Annual Mean PM2.5 (µg/m³)	WHO PM10 Limit Exceedance (%)	WHO PM2.5 Limit Exceedance (%)	Peak Period
2022	108 ± 8.5	66 ± 4.1	+116%	+164%	**April - May**
2023	96 ± 7.2	61 ± 3.8	+92%	+144%	**July - August**
2024	102 ± 7.8	64 ± 3.9	+104%	+156%	**March - May**

Comparison with WHO Guidelines: Recorded mean concentrations starkly exceeded the WHO safe limits (50 µg/m³ for PM10 and 25 µg/m³ for PM2.5) throughout the study period, with PM10 exceedances ranging from 92% to 116% and PM2.5 exceedances from 144% to 164%.

Analysis of Variance (ANOVA): A one-way ANOVA test comparing mean concentrations across the three years yielded a P-value > 0.05. This indicates no statistically significant difference between the annual means, confirming the persistence of chronic pollution without real improvement in air quality levels during the study period.

Table 2. Seasonal Variation in Particulate Concentrations.

Year	Season	Seasonal Mean PM10 (µg/m³)	Seasonal Mean PM2.5 (µg/m³)
2022	Winter	75	42
	Spring	122	76
	Summer	135	81
	Autumn	100	59
2023	Winter	68	40
	Spring	109	71
	Summer	126	79
	Autumn	88	52
2024	Winter	70	44
	Spring	118	74
	Summer	130	80
	Autumn	96	60

Table 3. Health and Environmental Impact.

Year	Respiratory Cases Reported	Soil pH Change (%)	Crop Yield Reduction (%)	Public Complaints Filed
2022	512	-8.2	-12.5	34
2023	489	-7.6	-11.3	29
2024	503	-7.9	-11.9	31

Table 4: Mitigation Measures Effectiveness Evaluation.

Year	Mechanical Filters	Water Spraying	Green Buffers	PPE Usage	Monitoring Protocols	Total
2022	5	4	3	6	5	**23**
2023	6	5	4	7	6	**28**
2024	7	5	6	8	7	**33**
(Scale: 1 = Very Poor Implementation, 10 = Excellent Implementation).						

Statistical and Seasonal Analysis

- Pooled Seasonal Mean (All Years Combined):
- Winter: PM10 = 71 µg/m³, PM2.5 = 42 µg/m³
- Spring: PM10 = 116.3 µg/m³, PM2.5 = 73.6 µg/m³
- Summer: PM10 = 130.3 µg/m³, PM2.5 = 80 µg/m³
- Autumn: PM10 = 94.6 µg/m³, PM2.5 = 57 µg/m³

Analysis of Variance (ANOVA): One-way ANOVA for comparison between seasons revealed a highly statistically significant difference between mean concentrations across seasons, with a P-value = 0.003 for both PM10 and PM2.5.

Post-Hoc Test: The test confirmed that the mean concentrations in Summer and Spring were significantly higher than those in Autumn a nd Winter.

Pearson Correlation Coefficient: Analysis showed a very strong positive correlation between PM10 and PM2.5 concentrations across all seasons, with a correlation coefficient of $r = 0.98$, indicating that these pollutants are emitted and move together in the environment.

Statistical Impact Analysis:

Dust-Health Relationship (Regression Analysis):

Multiple linear regression analysis, controlling for temperature and humidity, confirmed a strong positive relationship between PM2.5 concentration and respiratory cases. The overall model was significant ($p < 0.001$) with an adjusted R^2 of 0.85. The coefficient for PM2.5 was 4.8 (95% CI: 3.9 - 5.7), indicating that for every 1 µg/m³ increase in PM2.5, approximately 4.8 additional respiratory cases are reported, after accounting for meteorological effects.
meteorological effects.
The initial simple linear regression yielded an R^2 of 0.87. Simple linear regression analysis revealed a strong positive linear relationship between the annual mean PM2.5 concentration and the number of reported respiratory illness cases.
The Coefficient of Determination (R^2) was 0.87, meaning that 87% of the variance in respiratory cases can be explained by the variation in PM2.5 concentration, approximately 5 additional respiratory cases are reported in the local community.

The obtained regression equation suggests that for every 1 μg/m³ increase in PM2.5 concentration, approximately 5 additional respiratory cases are reported in the local community.

Impact on Soil: Soil analysis showed a consistent and notable decrease in pH towards alkalinity at all sampling sites, with a cumulative mean decrease ranging from 7.6% to 8.2% compared to baseline data.

An Independent Samples T-test confirmed that the difference in pH values and yield before and after dust exposure was statistically significant ($P < 0.05$).

Impact on Agriculture:

Dust deposition was associated with a clear decline in crop productivity in the surrounding areas, with a recorded reduction ranging from 11.3% to 12.5%.

Trend and Effectiveness Analysis:

Total Implementation Score: The total score showed a gradual improvement from 23 in 2022 to 33 in 2024.

Time-Series Linear Regression: Linear regression analysis of the relationship between the year and the total score showed a statistically significant upward trend, with an average improvement rate of approximately +5 points per year.

Component Analysis: The categories of "PPE Usage" and "Mechanical Filters" showed the highest rates of improvement. The "Green Buffer Zones" category also saw a notable jump in 2024 due to the plantation of dust-tolerant shrub species.

Persisting Gap: Despite this improvement, the average scores remain in the "Moderate to Below Moderate" range, indicating that the current level of implementation is still insufficient to effectively control the critical pollution levels identified.

5. DISCUSSION

The study confirmed chronic air and soil pollution from the cement plant, consistent with regional studies. Seasonal factors (Ghibli winds) exacerbated the problem. The strong link between dust, respiratory diseases, and environmental degradation highlights the significant risks. Despite slight improvements in mitigation, inadequate monitoring infrastructure and enforcement remain major obstacles.

The findings of this study paint a concerning picture of the persistent pollution impacts from cement dust emissions at the Benghazi plant, confirming a chronic state of degraded air and soil quality and an elevated health burden on surrounding communities. These results not only provide quantitative confirmation of the local situation but also offer profound insights into seasonal dynamics and the efficacy of current mitigation policies.

5.1 Persistent Exceedance of Standards and Regional Consistency:

The systematic exceedance of WHO guidelines for PM10 and PM2.5, by margins ranging from 92% to 164%, reflects a serious environmental and public health failure. This chronic trend, reinforced by the lack of a statistically significant difference between annual means ($P > 0.05$), is entirely consistent with reports by Al-Tamimi et al. (2020) near cement plants in Saudi Arabia and Iraq, and with findings by Mokhtar et al. (2021) in Egypt. This regional similarity points to common root causes, most notably a lack of advanced emission control infrastructure, weak enforcement of environmental regulations, and outdated production technologies. The markedly higher exceedance rate for PM2.5 indicates a greater public health risk, given the superior ability of these smaller particles to penetrate deep into the lungs and bloodstream.

5.2 Seasonal Variation: The Role of Meteorological Factors as Pollution Amplifiers:

The study revealed a highly distinct seasonal pattern, with the highest concentrations recorded during spring and summer, peaking in alignment with the Ghibli wind season. The statistically confirmed results (P = 0.003 from ANOVA) leave no doubt about the influence of meteorological factors. These hot, dry winds cause the resuspension and long-range transport of deposited dust, significantly expanding the geographical impact zone of the plant. This aligns with the conclusions of Hussein and Ahmed (2019) regarding the exacerbation of dust pollution in arid climates. Consequently, uniform year-round mitigation strategies appear insufficient, and seasonal emergency plans involving intensified water spraying and public health advisories during these peak periods must be designed.

5.3 Health Burden: Strong Evidence for a Causal Link:

The multiple regression analysis, which controlled for key meteorological confounders, strengthens the evidence for a causal link. The robust model (adjusted $R^2 = 0.85$) quantitatively and unequivocally linked exposure to PM2.5 with increased respiratory morbidity. The regression coefficient of 4.8 (95% CI: 3.9 - 5.7) suggests a dose-response relationship, where even minor increments in pollution contribute to worsening the health burden on the local healthcare system. This confirms the findings of Salem et al. (2022), WHO (2021) and Yousef et al. (2019) on the serious health effects of long-term exposure to fine particulates. The high and stable number of cases (~500 annually) suggests the community is suffering from a silent epidemic of chronic pollution-related respiratory diseases.

5.4 Environmental Degradation: A Long-Term Threat to Food Security:

The statistically significant decline in soil pH ($P < 0.05$) and agricultural productivity (~12%) provides tangible, physical evidence of environmental damage. The deposition of cement dust, rich in alkalis like CaO, disrupts the soil's delicate chemical balance, reducing the availability of essential plant nutrients and causing plant stress. This pathway of environmental degradation was previously documented by Hussein and Ahmed (2019) in Sudan and Tunisia. In a region like Benghazi, where peri-urban agriculture supports many households, this decline in yield threatens not only local income but also medium-term food security.

5.5 Mitigation Effectiveness: Marginal Progress vs. Systemic Challenges:

While the scoring matrix, now based on an adapted standardized framework, showed a positive trend, this progress remains fundamentally insufficient. The notable improvement in PPE usage indicates increased occupational safety awareness but addresses the symptom, not the root cause. Similarly, the slight improvement in mechanical filter efficiency is not supported by a continuous monitoring system capable of detecting real-time failures or exceedances. The relative weakness in implementing green buffers before 2024 points to a neglect of low-cost, ecologically-based solutions proven effective in dust interception, as noted by Alghamdi (2023). The gap between mitigation efforts and persistent pollution levels underscores that the solution lies not in isolated initiatives but in adopting an integrated, holistic approach encompassing advanced technology and stringent oversight.

5.6 Feasibility and Economic Considerations:

The proposed technical solutions, such as Electrostatic Precipitators (ESPs) and Baghouse Filters, must be evaluated for their economic viability within the Libyan context. While ESPs have high initial capital costs, they are generally more efficient for handling high-temperature gases and large gas volumes with lower operational costs over time, making them suitable for key production units like the kiln. Baghouse (fabric) filters, though potentially less expensive to install, offer superior collection efficiency for fine particles like PM2.5 but may have higher maintenance and replacement costs for the filter bags, especially in dusty environments. A hybrid system or a phased implementation plan could be considered. The cost-effectiveness of these technologies has been demonstrated in long-term studies, such as Guan et al. (2022) and Islam et al. (2024). which found that the health benefits and avoided environmental damage outweigh the investment costs. For the Benghazi plant, a detailed cost-benefit analysis is recommended, potentially starting with baghouse filters at critical emission points like crushers and mills, which are major sources of fugitive dust. Low-cost interventions, such as expanding green belts and optimizing water spraying systems, offer immediate, cost-effective complementary measures with proven co-benefits for the local environment.

5. 7 Implications and Proposed Policies:

These findings urgently call for radical policy reform. The approach must shift from being reactive to proactive. This requires:

- Enforcing mandatory emission standards based on WHO guidelines.
- Investing in real-time, continuous monitoring technologies for immediate detection of exceedances.
- Conducting independent, quarterly environmental audits with public disclosure of results.
- Integrating health and environmental impact assessments into industrial operating licenses.

6. CONCLUSION

The findings emphasize the urgent need for an integrated approach encompassing engineering improvements (advanced filters), nvironmental interventions (green buffers), and enhanced regulatory oversight and real-time monitoring to protect human health and the ecosystem in Benghazi and similar settings.

This study concludes that the Benghazi Cement Plant is a major and persistent source of air and soil pollution, posing a serious and direct threat to public health and environmental sustainability in the Benghazi region. The persistent exceedance of international standards, the clear link between dust and adverse health and environmental outcomes, and the inadequacy of current mitigation measures are facts that sound a strong alarm. Consequently, there is an imperative need to shift from monitoring and assessment to the effective implementation of radical solutions. Tangible improvement can only be achieved through adopting an integrated strategy that combines technological upgrades (advanced filters, real-time monitoring), application of environmental solutions (green buffers), stringent regulatory oversight and law enforcement, coupled with effective community oversight to ensure accountability and transparency.

7. SUMMARY

This study provided a comprehensive, longitudinal analysis of pollution from cement dust at the Benghazi Plant from 2022 to 2024. The results demonstrated chronic air pollution, with mean PM10 and PM2.5 concentrations exceeding WHO guidelines by more than double, without significant improvement over the study years. A sharp seasonal pattern was revealed, with peak risk during spring and summer due to the Ghibli winds. The study quantitatively documented a strong relationship between dust exposure and increased rates of respiratory illnesses (adjusted $R^2 = 0.85$ from multiple regression), alongside significant degradation of soil fertility and agricultural productivity. Although a slight improvement in the implementation of mitigation measures was recorded, it remained insufficient to control the problem, underscoring the need for more stringent and integrated interventions.

8. RECOMMENDATIONS

Based on the stark findings and in-depth analysis of this study, the following recommendations are urgently proposed to address the pollution crisis caused by the Benghazi Cement Plant, categorized into multiple levels of action:

I. Technical and Engineering Recommendations (Plant Level):

1. **Upgrade to Advanced Filtration Technologies:** Immediate investment in the installation and operation of high-efficiency air filtration systems, such as modern **Electrostatic Precipitators (ESPs)** and **Baghouse Filters**, with regular maintenance to ensure an efficiency of no less than 99.9% in capturing fine particulates.
2. **Implement Automated Dust Suppression Systems:** Widespread adoption of Smart Spraying Systems at key emission points (e.g., crushers, raw mills, loading/unloading points), activated automatically based on dust sensor readings to achieve higher water-use efficiency.
3. **Establish and Enhance Integrated Green Belts:** Expand the creation of a multi-row green buffer zone around the plant's perimeter using native, dense-foliage, and dust-tolerant trees and shrubs (e.g., Acacia, Olive). This must include an integrated irrigation and sustainable maintenance system.

II. Legislative and Oversight ecommendations

(Governmental and Regulatory Level):

4. **Enact and Enforce Mandatory Emission Standards:** Establish legally binding maximum emission limits for particulates (PM10 & PM2.5) based on WHO guidelines, and integrate them as a prerequisite for renewing the plant's environmental license.
5. **Create a National Real-Time Public Monitoring Network:** Install real-time continuous air quality monitoring stations at fixed locations around the plant and in adjacent residential areas, with data made instantly and publicly available on an online platform to ensure transparency and enable public accountability.
6. **Mandate Periodic Environmental Audits:** Impose mandatory independent environmental audits every 6 months by a specialized third party, encompassing emission assessments, worker health checks, and reviews of mitigation effectiveness, with results publicly disclosed.

III. Administrative and Community Recommendations (Plant Management and Community Level):

7. **Enhance Occupational Health and Safety Programs:** Implement a mandatory and sustainable occupational safety program, including the provision of high-quality Personal Protective Equipment (PPE) like N95 respirators, regular worker training on their correct use, and periodic medical screenings for early detection of respiratory diseases.
8. **Adopt the "Extended Social Responsibility" Principle:** The plant should fund and launch a corporate social responsibility program focused on compensating environmentally affected stakeholders, supporting the impacted local agricultural sector, and investing in projects to improve local environmental quality (e.g., creating public green spaces).
9. **Activate the Community's Oversight Role:** Facilitate clear communication channels between the local community and the regulatory body for reporting excessive emissions, ensure the right to access environmental information, and include community representatives in environmental monitoring committees.

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