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EXPOSURE TO AIRBORNE PARTICULATE IN AGRICULTURE SETTINGS AND ITS IMPACT ON WORKER PERFORMANCE UNDER CHANGING CLIMATE CONDITIONS

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Abstract

Introduction: *The effect of air pollution through particulates on farm workers in agricultural settings remains a key occupational hazard that farm workers face, particularly in fluctuating climates. However, there has been little research carried out on how exposure to particulates affects workers' efficiency. This study aims to assess the effects of particulates ($PM_{2.5}$ and PM_{10}) on performance, taking into consideration the effects of temperature as well as relative humidity.* ***Methods:*** *A cross-sectional survey was conducted on 150 farm workers working under typical dusty conditions. The particulate exposure was measured by a hand-held air quality meter. The work performance was then assessed by work speed, accuracy and fatigue level with a Borg Rating of Perceived Exertion scale. Descriptive analysis, correlation analysis, and linear multiple regression were used for data analysis.* ***Results and Discussion:*** *The results reported constant exposure to higher levels of particulates in an agricultural setting. The workers showed reasonably high accuracy in completing their tasks even though they were moderately to highly fatigued. This indicates that they adapted to environmental stressors. $PM_{2.5}$ and temperature were found to be important independent predictors associated with reduced worker performance, but there was no significant relationship between relative humidity and worker performance. The joint exposure to air pollution and thermal stress may influence worker performance.* ***Conclusion:*** *Exposure to particulate matter and thermal conditions may contribute to variations in worker performance in agricultural settings. Occupational measures are needed to minimize exposure and maintain worker performance in the face of environmental and climate challenges.*

INTRODUCTION

Air pollution continues to be a crucial environmental and occupational hazard across the globe, where particulate matter (PM), especially fine particles ($PM_{2.5}$), constitutes an important causative factor for diseases on a global scale (1). Exposure to $PM_{2.5}$ can lead to morbidity and mortality, as the fine particles can reach the alveolar level within the lungs and become distributed throughout the body (2). Previous research was carried out on urban and industrial environments, but agricultural settings provide a new area of investigation. Employees are exposed to airborne particulates because of soil tillage, agricultural operations and agrochemical usage (3). Such exposure occurs continuously, is poorly

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managed, and occurs in open environments, making its management particularly difficult (4–5). Employees engaged in intensive agriculture are usually involved in outdoor work at various times, leading to increased exposure levels and physiological burdens. There is inadequate empirical evidence about occupational exposure to PM in tropical agricultural environments.

Exposure to $PM_{2.5}$ has been associated with negative health outcomes, such as respiratory and cardiovascular disorders (6). However, studies have shown that exposure to pollutants can affect the performance of workers, in addition to causing various clinical effects. Air pollution has been associated with poor cognitive performance, decreased decision-making abilities, attention deficiencies, and lower worker performance (6–7). This is especially true for agricultural workplaces, where workers perform strenuous activities that require constant attention, coordination, and quick decision-making. Poor worker performance in such agricultural operations may be associated with reduced performance, decreased accuracy, and a higher risk of occupational injuries. This problem gains relevance in view of climate change. Climate change, alterations in rainfall, and an increase in the frequency of extreme weather events are likely to have an impact on the creation of PM and its dispersion behavior as well as the vulnerability of outdoor workers to such pollution (8–9). An increased level of temperature and aridity leads to greater dispersal of dust particles, while chemical reactions involving pollution formation and transport are directly associated with temperature changes. High temperatures may influence the ability and endurance of outdoor workers. Moreover, the combined exposure to PM and high temperatures may contribute to adverse health outcomes and lower worker performance. Humidity plays an important role in controlling the activity of particles and affects particle aggregation, deposition, and inhalation (10–11). In this study, the term "worker performance" refers to the ability of agricultural workers to complete tasks efficiently and accurately under environmental exposure conditions. Worker performance was evaluated using task completion time, work accuracy, and fatigue level during agricultural activities. The term was used consistently throughout the study to represent functional work outcomes under particulate and climate exposure conditions.

The above findings indicate a substantial gap in the literature in this domain. This gap lies in the non-integrated examination of exposure to PM, performance effects on the laborers, and the effect of weather elements. Prior literature has been largely concerned with how exposure affects the health of affected subjects without considering the functional aspects of the same. In addition, not enough field data exists concerning real-life exposure among laborers in tropical agriculture. (12–13). This research seeks to determine the influence of occupational exposure to air particulates ($PM_{2.5}$ and PM_{10}) on worker performance in agricultural settings under different climatic conditions, with emphasis on the contribution of temperature and humidity. Occupational exposure to particulates ($PM_{2.5}$ and PM_{10}) is expected to have a negative impact on worker performance, which could be measured using physical and work-based measures. Besides, climatic factors such as temperature and humidity are expected to show considerable influence.

METHODS

Cross-sectional studies were conducted in chosen agricultural settings where the regular occurrence of dust production due to activities such as harvesting, land preparation, and cultivation of soil took place. Study participants comprised farmworkers aged 18 years and older who had six months or more of working experience. People suffering from chronic illnesses involving their respiratory and cardiovascular systems were not considered for the study. The purposive sampling approach was used in order to incorporate participants involved in dust-producing agricultural operations. For the correlation and multiple regression analyses, power analysis was conducted through the use of G*Power Software by estimating the sample size using the medium effect size ($f^2 = 0.15$), significance level ($\alpha = 0.05$), and statistical power ($1 - \beta = 0.80$). A minimum of 92 respondents were required for the study. However, 150 farmers were used in this experiment to allow for non-response and to enhance the validity of the analysis (14).

Particulate matter ($PM_{2.5}$ and PM_{10}) exposure in the air was determined as the independent variable, with the measure for the variable expressed in μg/m³. As for the dependent variable, worker performance was assessed using task completion time, work accuracy, and fatigue level. Higher work accuracy and shorter task completion time represented better worker performance, while higher fatigue scores represented lower worker performance. The indicators were evaluated collectively to represent overall worker performance under environmental exposure conditions. Environmental temperature (C) and relative humidity (%) were also computed. The other covariate variables considered are age, employment duration, alcohol consumption and PPE utilization. The work performance was estimated by a structured observation form where the time of completion and accuracy of work were recorded. Fatigue perception was predicted by Borg Rating of Perceived Exertion (RPE) scale which had been widely used in previous studies. The range of the scores had a value of 6 to 20; the higher value, the higher the fatigue. The observations were done by trained observers with standardized procedures for reliability.

Concentrations of total suspended particles ($PM_{2.5}$ and PM_{10}) in the air were quantified using a pre-calibrated portable air quality monitor. Before data collection, the monitor was calibrated following the manufacturer's guidelines (15). Measurements were taken during active hours only while on the job, and were averaged over an 8-hour window and reported as time-weighted averages (TWA). Sampling occurred at the worker's breathing zone to represent personal exposure. The ambient temperature (°C) and relative humidity (%) were recorded every 5 min, using a digital environmental meter. The results were then computed on the working duration to show the exposure conditions. Climate measures were taken with the sampling of particulates during worker activity periods ensuring the accurate measurement of exposures. Temperature and humidity were also recorded using a digital environmental meter.

Before analysis began, the data quality was checked carefully. Any record with missing values or incomplete observations was removed from the dataset. Statistical measures identified outliers, and we discarded them when measurement error or technical failure caused them. Normality, linearity, as well as consistency were also checked before the analysis. The Pearson correlation and regression were assessed using histograms, normal probability plots, and scatterplots. Before multiple regression analysis, we first evaluated the statistical assumptions. We checked residual normality, linearity, and multicollinearity to confirm that the regression model was suitable. During the workers' activities, observation took place. Particulate matter and climatic conditions were measured at the same time, while worker performance was recorded immediately. Using statistical packages, we analyzed all data statistically and obtained descriptive statistics for each variable. Pearson correlation analysis was examined for the relation between particulates and worker performance. After adjusting for climatic conditions and covariates, multiple linear regression analysis assessed the association between particulate exposure and worker performance. The regression variables were then selected for their theoretical relevance and for findings from previous literature studies discussing occupational and environmental health. Variables presenting possible correlations from preliminary analysis were selected for inclusion to the final regression model. A p-value of less than 0.05 was considered statistically significant. This study was approved by the Institutional Research Ethics Committee (IREC-2025-111). All participants gave written informed consent before the experiment. All procedures adhered to the Helsinki Declaration.

RESULTS

The number of agricultural workers who took part in this study is 150 (response rate = 90.9%). All responses were used for the descriptive statistics. After data cleansing, missing values of 2.0% were deleted. The remaining case used for the multivariate analysis was 147. The low percentages of cases with missing values indicate higher data quality and reduced response bias. Particulate matter behaved with high dispersion in the air environment at the location. The mean $PM_{2.5}$ concentration for the study site was 48.6 ± 12.3 g/m^3 and PM_{10} was 92.4 ± 20.7 g/m^3. The median values were less than the means; this indicates asymmetric fields with higher concentration observations (Table 1). Also, 33.3% of $PM_{2.5}$ concentrations were over 55 g/m^3 and 40.0% of PM_{10} were more than 100 g/m^3. This suggests a potential for high particle exposure for farm workers, mainly of dust generating activities (Table 1). Workers had statistically significant differences in measured performance, which could be in response to different activity requirements or individual differences in reacting to the occupational environment (Table 2). The task completion time was 43.2 ± 8.5 min and 56.7% of workers performed the task in 36 to 50 min.

Table 1. Descriptive Characteristics of Study Variables

Variable	Mean ± SD	Median (IQR)	Min–Max
$PM_{2.5}$ (μg/m³)	48.6 ± 12.3	46.8 (39.2–55.7)	25.4–78.9
PM_{10} (μg/m³)	92.4 ± 20.7	89.5 (75.3–105.8)	50.2–140.6
Temperature (°C)	32.1 ± 2.8	32.0 (30.5–34.0)	27.5–37.0
Relative Humidity (%)	68.5 ± 8.2	69.0 (62.0–75.0)	50.0–85.0
Task Completion Time (min)	42.5 ± 8.6	41.0 (36.0–48.0)	25–65
Fatigue Score	13.2 ± 3.1	13.0 (11.0–15.0)	7–20
Work Accuracy (%)	86.4 ± 6.8	87.5 (82.0–92.0)	70–98

This pattern suggests that the majority of workers had completed tasks at a steady pace. However, some minor variation remained. Accuracy was relatively high, at 84.5 ± 7.2% on average. In total, 83.4% of workers reached at least 80% accuracy. Even with environmental exposure, most respondents still performed their jobs in a satisfactory manner. Based on the Borg RPE scale used, the fatigue index was 13.8 ± 2.9, which indicates moderate fatigue. In total, 23.3% of respondents fell into the high-fatigue group. A meaningful share of workers likely experienced physical fatigue while completing their tasks. This difference in fatigue could affect performance outcomes in stressful environments. The correlation analysis reported a negative correlation among being exposed to air particulates and the performance of workers (Table 3). $PM_{2.5}$ and PM_{10} were analyzed, and $PM_{2.5}$ had a stronger association with worker performance. For this reason, the regression interpretation and discussion mainly focused on $PM_{2.5}$ as the primary predictor in the final model.

Table 2. Distribution of Study Variables by Category

Variable	Category	Frequency (n)	Percentage (%)
$PM_{2.5}$ (μg/m³)	≤ 35	28	18.7
	36–55	72	48.0
	> 55	50	33.3
PM_{10} (μg/m³)	≤ 50	12	8.0
	51–100	78	52.0
	> 100	60	40.0
Task Completion Time	≤ 35 min	30	20.0
	36–50 min	85	56.7
	> 50 min	35	23.3
Fatigue Score	Low (≤ 10)	25	16.7
	Moderate (11–15)	90	60.0
	High (> 15)	35	23.3
Work Accuracy (%)	≥ 90	55	36.7
	80–89	70	46.7
	< 80	25	16.7
Temperature (°C)	≤ 30	35	23.3
	31–34	80	53.3
	> 34	35	23.3
Humidity (%)	≤ 60	30	20.0
	61–75	85	56.7
	> 75	35	23.3

There was a negative correlation between the exposure to $PM_{2.5}$ particulates and performance ($r = -0.42$, $p < 0.001$), suggesting an association between higher levels of particulate exposure and lower performance. This was consistent with the general trend observed for $PM_{2.5}$ which is known to cause increased strain on the body. Temperature showed a negative correlation with the performance of workers ($r = -0.35$, $p < 0.001$), indicating that higher temperatures may be associated with poorer worker performance. However, the relative humidity did not have a significant effect on worker performance ($r = -0.12$, $p = 0.143$).

Table 3. Relationship Between Particulate Exposure and Worker Performance

Variables	Worker Performance (r)	p-value
$PM_{2.5}$ (μg/m³)	−0.42	< 0.001
PM_{10} (μg/m³)	−0.38	< 0.001
Temperature (°C)	−0.35	< 0.001
Relative Humidity (%)	−0.12	0.143

The multiple linear regression was adopted to assess this relationship. After controlling for all other factors, it emerged that the concentration level of $PM_{2.5}$ acted as an independent statistical determinant for work inefficiency ($\beta = -0.31$, SE = 0.10, $p = 0.002$). In addition, temperature was significantly associated with lower worker performance ($\beta = -0.27$, SE = 0.09, $p = 0.004$). In addition, these coefficient estimates were of a similar magnitude and direction. This implied robustness of findings from these independent predictors. The model explained 38% of variation in worker performance ($R^2 = 0.38$; Table 4). This indicates that additional occupational, behavioral, and individual factors may also contribute to worker performance outcomes. There was no indication of multicollinearity among predictors. Residual analysis showed no major violation of regression assumptions. The residuals were approximately normally distributed, and no serious heteroscedasticity or influential outliers were detected. Preliminary diagnostic assessment indicated no major violation of normality or linearity assumptions for Pearson correlation analysis.

Table 4. Analysis of Factors Affecting Worker Performance Using Multiple Linear Regression

Variable	β	SE	t-value	p-value	95% CI
$PM_{2.5}$ (μg/m³)	−0.31	0.10	−3.10	0.002	−0.51 to −0.11
Temperature (°C)	−0.27	0.09	−2.95	0.004	−0.45 to −0.09
Humidity (%)	−0.08	0.07	−1.25	0.210	−0.22 to 0.05
Age (years)	−0.05	0.06	−0.97	0.332	−0.17 to 0.06
Work Duration (years)	−0.04	0.05	−0.84	0.401	−0.14 to 0.05
Smoking Status	−0.06	0.05	−1.07	0.287	−0.16 to 0.04
PPE Use	0.09	0.06	1.57	0.118	−0.02 to 0.20

DISCUSSION

The agricultural microenvironment is a biological bottleneck, where the movement of particulates suspended in the air may create periods of increased exposure risk that cannot be detected using standard ambient measurements. Though there are air quality stations in place for monitoring the air quality at the regional level, the consistently high levels of $PM_{2.5}$ observed at the site suggest that agricultural workers are subjected to constant exposure to a respiratory barrier. Instead of merely recognizing the poor quality of air in the region, the study's findings suggest that existing OSH management systems may be insufficient for the episodic and situational context of developing tropical countries. High-level exposure events occurring during dust-generating activities may create periods of increased exposure risk. Therefore, task-based monitoring approaches may provide useful additional information compared to centralized environmental monitoring data. This suggests that workers may be experiencing physiological strain while maintaining task performance. One possible explanation for the observed high work accuracy despite moderate-to-high fatigue levels is that workers may continue performing tasks under physiological strain. This finding may reflect adaptive work behavior in response to environmental exposure conditions, particularly during physically demanding agricultural activities (16–18).

Fine particles may be associated with reduced worker performance through respiratory and cardiovascular strain may cause mild irritation, which results in mental fatigue and physical exhaustion. This result is confirmed by findings of, whose study demonstrated how harmful the effects of outdoor air pollution are for labor productivity even at non-lethal levels (19). The findings suggest that particulate exposure may have a stronger association with worker performance than humidity levels. Increased temperature level can contribute to faster breathing and higher particulate intake when performing strenuous activities. This relationship shows the importance of considering environmental factors.

This consistent performance accuracy, even with low variability in performance completion time, shows that the agricultural laborers can adopt compensatory strategies in order to perform tasks in an environment that is characterized by occupational stressors like exposure to particulate matter. While the majority of the participants showed high performance accuracy (≥ 80%), the variation in performance completion time signifies the adoption of a slower rate of task completion to ensure accuracy. This behavioral pattern is similar to the results of recent occupational ergonomics studies, indicating that laborers exposed to environmental stressors may adjust their working speed to maintain accuracy to avoid physiological strain and cognitive overload (20–21).

The moderately high RPE score (mean RPE ≈13.8) alongside a relatively high percentage of workers exhibiting fatigue (23.3%) emphasizes the importance of physiological strain as a mediator. Several recent studies on occupational health demonstrate that fatigue may be associated with reduced endurance and work efficiency over time when performing a given task, especially those involving physical work in agriculture (21–22). This could explain why performance accuracy remained unaffected despite the increasing variability in task completion time.

Employees who regularly work within a polluted environment may develop adaptive physiological and behavioral responses which may help them maintain. This can be done by pacing themselves, prioritizing their tasks, and increasing resistance to environmental pressures. But this does not mean that there are no dangers involved since workers may still experience physical strain even though they can work effectively. Workers' abilities to maintain task performance can mask physiological strain. The findings show that fine particulate matter ($PM_{2.5}$) as an environmental factor is significantly associated with worker performance, which is supported by biological and occupational health evidence (22–23). Fine particles can also penetrate deeply inside the lungs and broader body system. This may contribute oxidative stress, inflammation, and neurophysiological dysfunction. The pathways have shown consistent associations with poor cognitive functioning, decreased attention span, and slow psychomotor responses, all of which may influence performance and decision-making abilities (24–25). Previous research shows that low to moderate levels of exposure to $PM_{2.5}$ have been associated with to observable changes in cognitive abilities, especially those that require focused attention and accuracy (26–27).

Environmental factors such as high temperatures have been reported to play an important role in shaping occupational outcomes, specifically through physiological strain such as dehydration, increased heart rate, and poor thermoregulation which may contribute to lower endurance and fatigue. Humidity has shown a statistically insignificant relationship since it has minimal bearing on job productivity as opposed to being an independent stressor. However, humidity levels have a direct impact on thermal perception and comfort during breathing, depending on the interrelationship with temperature. Recent studies in environmental health suggest that humidity may not act as an independent factor associated with worker performance since it acts either as a stress modifier or co-factor alongside other environmental stressors. The high temperatures were significantly correlated with reduced work productivity in occupations that take place in open environments, such as outdoor and agricultural industries, where there is limited scope for adopting coping measures. In addition, heat has been associated with cognitive impairment, reinforcing the idea that environmental stressors may influence both physical and mental aspects of work.

The findings suggest that environmental factors such as particulate exposure and temperature may contribute to variations in worker performance, although other occupational and individual factors may also play important roles. However, while the presence of environmental factors may account for some degree of variability in worker performance, other variables related to individual differences could play a moderating role as per occupational health theories. Therefore, any intervention should take into consideration the interaction between environmental and worker-based factors in order to improve worker performance.

There are several constraints that must be noted in interpreting the results from this analysis. First, the cross-sectional design of this study limits the ability to identify causal associations between environmental exposure and worker performance. Although there are ample scientific evidence and biological plausibility supporting the association, a deeper understanding of the temporal dynamics of environmental exposure and its effect on the outcome cannot be fully captured. Second, the measurement of environmental factors was likely conducted at specific points in time and could not capture variations in exposures within the day. The potential for exposure misclassification due to changes in particulate matter concentration and temperature cannot be ruled out. Third, individual characteristics were not accounted for as confounders in this study, although they affect fatigue and performance. Fourth, the possibility of healthy worker bias should also be considered in interpreting the findings. Workers who remained actively employed in agricultural activities may have been physically healthier or more adapted to environmental exposure compared to individuals who had left the occupation due to health-related reasons. Therefore, the observed associations may underestimate the actual impact of particulate exposure on worker performance. Nevertheless, these limitations do not substantially affect the overall interpretation of the findings. The agreement of the results with known physiological mechanisms and the latest scientific evidence contributes to the validity of the discovered associations. In addition, the lack of multicollinearity and the stability of environmental factors imply the independent nature of these variables, which makes them even more relevant as key drivers of worker performance. Further investigations could benefit from adopting longitudinal approaches, using real-time measures of environmental exposures, and accounting for personal vulnerability to environmental stressors.

CONCLUSION

Results suggest that environmental exposure (mainly $PM_{2.5}$) and temperature can factor into changes in worker performance in agriculture. Workers were able to sustain work accuracy with moderate fatigue, which illustrates adaptation effects linked to physically demanding work. There were no significant findings between relative humidity and worker performance. This study shows empirical evidence that environmental exposure conditions have an effect on worker performance in agriculture. Therefore, minimizing environmental exposure levels in the work place can contribute to supporting sustainable worker performance in the agriculture industry.

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AUTHORS' CONTRIBUTION

NY: Conceptualization, Methodology, Supervision, Writing, Reviewing. ANA: Data curation, Investigation, Writing, Original draft preparation. HNN: Methodology, Data analysis, Writing, Original draft preparation. NFAR: Data curation, Validation, Visualization. SS: Investigation, Data analysis. RR: Validation, Writing, Reviewing and Editing.

REFERENCES

1. Manrique A, Clarke K, Bisesi S, Arosemena FA, Coker ES, Sabo-Attwood T. The Adverse Health Effects of Air Pollution from Sugarcane Burning: A Scoping Review of Observational and Experimental Evidence. *Environmental Health Perspectives*. 2025;133(1):1–16. https://doi.org/10.1289/EHP14456
2. Ismail NA, Abdullah S, Mansor AA, Ahmad AN, Ahmed AN, Ismail M. Trend and Interrelationship of $PM_{2.5,}$ Gaseous Pollutants and Meteorological Factors in Kuala Terengganu, Malaysia. *International Journal of Design & Nature and Ecodynamics*. 2024;19(4):1251–1260. https://doi.org/10.18280/ijdne.190416
3. Inlaung K, Chotamonsak C, Macatangay R, Surapipith V. Assessment of Transboundary $PM_{2.5}$ from Biomass Burning in Northern Thailand Using the WRF-Chem Model. *Toxics*. 2024;12(7):1–15. https://doi.org/10.3390/toxics12070462
4. Al-Battawi S, Latif MT, How V, Thilakavathy K, Hamid HHA, Tan CK, et al. Effect of Traffic Volumes on Polycyclic Aromatic Hydrocarbons of Particulate

Matter: A Comparative Study from Urban and Rural Areas in Malaysia. *PLoS One*. 2024;19(12):1–26. https://doi.org/10.1371/journal.pone.0315439

5. Garcia A, Santa-Helena E, Falco AD, Ribeiro JdP, Gioda A, Gioda CR. Toxicological Effects of Fine Particulate Matter ($PM_{2.5}$): Health Risks and Associated Systemic Injuries—Systematic Review. *Water, Air, & Soil Pollution*. 2023;234(346):1–23. https://doi.org/10.1007/s11270-023-06278-9
6. Basith S, Manavalan B, Shin TH, Park CB, Lee WS, Kim J, et al. The Impact of Fine Particulate Matter 2.5 on the Cardiovascular System: A Review of the Invisible Killer. *Nanomaterials*. 2022;12(15):1–28. https://doi.org/10.3390/nano12152656
7. Thangavel P, Park D, Lee YC. Recent Insights into Particulate Matter ($PM_{2.5}$)-Mediated Toxicity in Humans: An Overview. *International Journal of Environmental Research and Public Health*. 2022;19(12):1–22. https://doi.org/10.3390/ijerph19127511
8. Wu B, Yan T, Elahi E. The Impact of Environmental Pollution on Labor Supply: Empirical Evidence from China. *Environmental Science and Pollution Research*. 2023;30:25764–25772. https://doi.org/10.1007/s11356-022-23720-3
9. Salem A, Zahran A, Allam A. The Impact of Air Pollutants on Oil Industry and Its Relation to Safety and Occupational Health Inside the Working Environment (Case Study in Elhadisa Extraction Mill). *International Journal of Environmental Studies and Researches*. 2022;1(2):194–204. https://doi.org/10.21608/ijesr.2022.296774
10. Ye HJ, Huang Z, Chen S. Air Pollution and Agricultural Labor Supply: Evidence from China. *China Economic Review*. 2023;82(102075):1–24. https://doi.org/10.1016/j.chieco.2023.102075
11. Hong A, Choi DA, Chung H, Kumar P, Lee J. Environmental and Health Monitoring in Smart Cities: A Systematic Review of Trends, Opportunities, and Challenges. *Sustainable Cities and Society*. 2025;130(106491):1–12. https://doi.org/10.1016/j.scs.2025.106491
12. Mohammadi MJ, Dehaghi BF, Mansourimoghadam S, Sharhani A, Amini P, Ghanbari S. Cardiovascular Disease, Mortality and Exposure to Particulate Matter (PM): A Systematic Review and Meta-Analysis. *Reviews on Environmental Health*. 2024;39(1):141–149. https://doi.org/10.1515/reveh-2022-0090
13. Wang S, Song R, Xu Z, Chen M, Tanna GLD, Downey L, et al. The Costs, Health and Economic Impact of Air Pollution Control Strategies: A Systematic Review. *Global Health Research and Policy*. 2024;9(30):1–12. https://doi.org/10.1186/s41256-024-00373-y
14. Althubaiti A. Sample Size Determination: A Practical Guide for Health Researchers. *Journal of General and Family Medicine*. 2023;24(2):72–78. https://doi.org/10.1002/jgf2.600
15. Cavalcante RM, Santos R, Furtado LS, Gurjão NdO, Filho J, Silveira JA, et al. Low-Cost Sensors: Performance Test and Applications in Occupational Health Studies Related to Exposure to Respirable Particles. *Journal of Occupational and Environmental Hygiene*. 2026;23(4):219–229. https://doi.org/10.1080/15459624.2025.2589134
16. Mishra P, Parsons L. Rest in a Warming Workplace: Resituating the Science and Policy of Non-Work Under Climate Change. *Geo: Geography and Environment*. 2026;13(1):1–12. https://doi.org/10.1002/geo2.70070
17. Hill AE, Burkhardt J, Bayham J, O'Dell K, Ford B, Fischer EV, et al. Air Pollution, Weather, and Agricultural Worker Productivity. *American Journal of Agricultural Economics*. 2023;106(4):1329–1353. https://doi.org/10.1111/ajae.12439
18. Puvvula J, Baccaglini L, Johnson A, Du Y, Bell JE, Rautiainen RH. Prevalence and Risk Factors for Pulmonary Conditions among Farmers and Ranchers in the Central United States. *Journal of Agromedicine*. 2022;27(4):378–390. https://doi.org/10.1080/1059924X.2021.2025180
19. Agathokleous E, Blande JD, Calabrese EJ, Guedes RN, Benelli G. Stimulation of Insect Vectors of Pathogens by Sublethal Environmental Contaminants: A Hidden Threat to Human and Environmental Health? *Environmental Pollution*. 2023;336(122422):1–5. https://doi.org/10.1016/j.envpol.2023.122422
20. Pryor JT, Cowley LO, Simonds SE. The Physiological Effects of Air Pollution: Particulate Matter, Physiology and Disease. *Frontiers in Public Health*. 2022;10(882569):1–13. https://doi.org/10.3389/fpubh.2022.882569
21. López-Granero C, Polyanskaya L, Ruiz-Sobremazas D, Barrasa A, Aschner M, Alique M. Particulate Matter in Human Elderly: Higher Susceptibility to Cognitive Decline and Age-Related Diseases. *Biomolecules*. 2023;14(1):1–17. https://doi.org/10.3390/biom14010035
22. Behrens M, Gube M, Chaabene H, Prieske O, Zenon A, Broscheid KC, et al. Fatigue and Human Performance: An Updated Framework. *Sports Medicine*. 2023;53:7-31. https://doi.org/10.1007/s40279-022-01748-2
23. Srinidhi G, Agrawal KN, Kumari S, Potdar RR, Chandel NS, Rao KVR, et al. Muscle Fatigue Assessment Using Surface Electromyography in Farm Operations Performed in Protected Cultivation. *Scientific Reports*. 2025;15(33758):1–17. https://doi.org/10.1038/s41598-025-00144-w
24. Yasmeen R. A Comprehensive Review on PM, Gaseous and Biological Emissions: Monitoring Techniques, Health Impacts and Mitigation Strategies. *World's Poultry Science Journal*. 2025;81(4):1143–1168. https://doi.org/10.1080/00439339.2025.2563560
25. Wang W, Lin Y, Yang H, Ling W, Liu L, Zhang W, et al. Internal Exposure and Distribution of Airborne Fine Particles in the Human Body: Methodology, Current Understandings, and Research Needs. *Environmental Science & Technology*. 2022;56(11):6857–6869. https://doi.org/10.1021/acs.est.1c07051

26. Zhang J, Wang Y, Li Z, Peng J, Dai L, Li N, et al. Association between Low-Concentration $PM_{2.5}$ Exposure and Emergency Department Visits for Cardiovascular Diseases: A Time-Series Study. *Frontiers in Public Health*. 2025;13(1704279):1–11 https://doi.org/10.3389/fpubh.2025.1704279
27. Lee HM, Bae MS, Kim JH, Kim MW. Characteristics and Chemical Composition of $PM_{2.5}$ in Agricultural Regions: A Case Study in Jeonbuk-do, South Korea. *Air Quality, Atmosphere & Health*. 2025;18:3567–3580. https://doi.org/10.1007/s11869-025-01849-7