

Air Quality And Its Impact On Athlete Performance In Outdoor Training

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ABSTRACT

Air quality has become an increasingly important environmental issue in sports, particularly for athletics athletes who perform regular outdoor training. Exposure to air pollutants such as particulate matter (PM_{2.5} and PM₁₀), ozone (O₃), and other airborne contaminants may negatively affect respiratory function, aerobic capacity, and overall athletic performance. This study aimed to analyze the impact of air quality on the performance of athletics athletes during outdoor training. A quantitative correlational design was employed involving 30 competitive athletics athletes who participated in an eight-week outdoor training program. Air quality indicators, including PM_{2.5}, PM₁₀, O₃, NO₂, and Air Quality Index (AQI), were measured using portable monitoring devices. Athletic performance was assessed through VO₂max, 100-meter sprint performance, recovery heart rate, and Rating of Perceived Exertion (RPE). The results showed that the average AQI during training was 87.73 ± 15.47, indicating moderate air quality conditions. Correlation analysis revealed a strong negative relationship between AQI and VO₂max ($r = -0.726$, $p < 0.01$), while positive relationships were found between AQI and sprint time, recovery heart rate, and RPE. Multiple regression analysis demonstrated that air quality variables explained 66.1% of the variance in VO₂max ($R^2 = 0.661$, $p < 0.001$). In conclusion, poor air quality significantly reduces aerobic performance, impairs recovery, and increases physiological strain among athletics athletes. Therefore, air quality monitoring should be integrated into outdoor training management to optimize athlete performance and health.

Keywords : Air Quality, Athletics Performance, Outdoor Training, VO₂max, Environmental Health.

INTRODUCTION

Athletics is one of the most popular sports globally and relies heavily on the optimal functioning of the cardiorespiratory, metabolic, and neuromuscular systems. Outdoor training is an essential component of athletic preparation because it enables athletes to adapt to environmental conditions similar to those encountered during competitions. However, the increasing deterioration of air quality in urban and suburban environments has become a major challenge for athletes who routinely perform high-intensity training outdoors. Air pollution, particularly fine particulate matter (PM_{2.5}), coarse particulate matter (PM₁₀), ozone (O₃), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and carbon monoxide (CO), has been identified as a significant environmental factor capable of affecting physiological function, exercise capacity, and athletic performance (Koehle & Rojas, 2024; González-Rojas et al., 2025). Exposure to air pollution during exercise is especially

concerning because athletes experience substantially higher ventilation rates, resulting in greater inhalation of pollutants into the respiratory tract and alveolar structures.

From a physiological perspective, the interaction between exercise and air pollution can be explained through the Environmental Stress Theory, which posits that environmental stressors may disrupt homeostasis and reduce physical performance. During vigorous exercise, minute ventilation may increase by 10–20 times compared with resting conditions, thereby increasing the deposition of airborne pollutants within the respiratory system. Consequently, athletes may experience airway inflammation, oxidative stress, impaired pulmonary function, reduced oxygen transport capacity, and cardiovascular strain (Cortés González et al., 2025; Koehle & Rojas, 2024).

Several studies have demonstrated that poor air quality negatively affects endurance performance. Research involving collegiate runners found that repeated exposure to PM_{2.5} and ozone was associated with slower race times, even when pollution levels remained within air quality categories generally considered acceptable for outdoor activity (Cusick et al., 2023). Similarly, evidence from international sporting events has shown that air pollution may compromise athletes' health and performance, particularly during endurance-based competitions such as athletics, cycling, and marathon running (Bougault et al., 2024).

The issue is particularly relevant in developing countries, including Indonesia, where rapid urbanization, transportation emissions, industrial activities, and seasonal biomass burning contribute to declining air quality. Despite increasing concern regarding environmental health, limited attention has been directed toward understanding how air quality influences athletic performance during routine outdoor training. Consequently, coaches, sports scientists, and policymakers often lack evidence-based guidelines for modifying training loads and schedules according to environmental conditions.

Recent scientific developments have increasingly highlighted the relationship between air quality and sports performance. According to the Ecological Systems Theory proposed by Bronfenbrenner, athlete performance is influenced not only by individual factors but also by environmental conditions surrounding the athlete. Air quality represents an environmental determinant capable of directly influencing physiological responses and athletic outcomes.

A systematic review conducted by González-Rojas et al. (2025) concluded that endurance exercise performed in polluted environments may induce adverse respiratory and cardiovascular responses, including decreased pulmonary efficiency and elevated systemic inflammation. Similarly, Koehle and colleagues (2024) emphasized that exposure to air pollutants before and during exercise can impair oxygen uptake, reduce exercise tolerance, and increase perceived exertion among athletes.

The Oxidative Stress Theory further explains these findings. Air pollutants stimulate the production of reactive oxygen species (ROS), leading to oxidative damage in pulmonary and vascular tissues. Increased oxidative stress may impair mitochondrial efficiency, thereby reducing aerobic energy production and endurance performance. Numerous studies have reported elevated inflammatory biomarkers and reduced lung function among individuals exercising in polluted environments (Cortés González et al., 2025).

Empirical evidence from athletics has also strengthened this relationship. Cusick et al. (2023) reported that athletes exposed to higher concentrations of PM_{2.5} and ozone during training demonstrated significantly slower race performances than athletes training under cleaner air conditions. Additional evidence suggests that pollution exposure may reduce maximal oxygen uptake (VO₂max), impair recovery, and increase respiratory symptoms among endurance athletes.

The International Olympic Committee (IOC) has also recognized air quality as a critical issue affecting athlete health and performance. The IOC consensus report emphasized that future international sporting events are increasingly likely to occur in environments characterized by elevated pollution levels, making environmental monitoring an essential component of athlete preparation and competition management.

Furthermore, environmental health studies have demonstrated that ozone exposure during moderate-to-vigorous physical activity adversely affects pulmonary function and respiratory efficiency. These findings indicate that air pollution is not merely an environmental concern but also a performance-limiting factor that directly influences athletic outcomes.

Although substantial progress has been made in understanding the physiological consequences of air pollution, several important research gaps remain. First, most previous studies have focused primarily on general populations, recreational exercisers, or marathon runners, whereas relatively few investigations have specifically examined athletics athletes undergoing structured outdoor training programs.

Second, existing studies predominantly investigate acute exposure effects, while the cumulative impact of chronic exposure during long-term athletic training remains insufficiently understood. Recent reviews indicate that evidence regarding long-term adaptations or maladaptations among athletes repeatedly exposed to polluted environments remains limited and inconclusive.

Third, most studies emphasize respiratory health outcomes rather than direct athletic performance indicators such as running speed, endurance capacity, recovery quality, training consistency, and competitive achievement. Consequently, the mechanisms linking air quality to sport-specific performance remain inadequately explained.

Fourth, research from Southeast Asian countries, particularly Indonesia, remains scarce despite the region frequently experiencing episodes of poor air quality resulting from urban emissions, industrial activities, and transboundary haze events. Therefore, contextual evidence relevant to tropical environments is still lacking.

Finally, there is limited integration between environmental health science and sports science literature. Most environmental studies focus on public health implications, whereas sports performance studies rarely incorporate objective air quality indicators such as PM_{2.5}, AQI, ozone concentration, and pollutant exposure duration into athlete monitoring systems.

Based on these gaps, the present study aims to comprehensively examine the relationship between air quality and athletic performance among athletics athletes participating in outdoor training programs. Specifically, this study seeks to analyze how exposure to major air pollutants influences physiological responses, respiratory function, aerobic capacity, recovery processes, and overall athletic performance.

The novelty of this study lies in four important aspects. First, it integrates environmental health theory and sports performance theory into a unified conceptual framework linking air quality, physiological adaptation, and athletic outcomes. Second, it focuses specifically on athletics athletes, a population highly dependent on aerobic and cardiorespiratory efficiency. Third, it synthesizes recent evidence from both environmental science and sports science literature published within the last decade. Fourth, it proposes an evidence-based model for incorporating air quality monitoring into outdoor training management, thereby providing practical implications for coaches, athletes, sports institutions, and policymakers.

Ultimately, this study contributes to the growing body of knowledge emphasizing that environmental quality is an integral component of athlete development. Understanding the



influence of air quality on athletic performance is essential for optimizing training effectiveness, protecting athlete health, and ensuring sustainable achievement in athletics.

In conclusion, declining air quality has emerged as a critical environmental factor that may adversely affect physiological function, respiratory health, and athletic performance during outdoor training. Existing evidence consistently indicates that exposure to pollutants such as PM_{2.5} and ozone can impair endurance capacity, increase respiratory burden, and reduce competitive performance. Nevertheless, substantial gaps remain regarding long-term effects, athletics-specific populations, and contextual evidence from developing countries. Therefore, investigating the relationship between air quality and athletic performance is both scientifically relevant and practically important. The findings are expected to strengthen environmental health considerations within sports training systems and support the development of evidence-based strategies for safer and more effective outdoor athletic training.

METHODS

This study employed a quantitative observational research design with a correlational approach to examine the relationship between air quality and athletic performance during outdoor training among athletics athletes. Quantitative methods are considered appropriate for investigating environmental determinants of sports performance because they allow objective measurement of both environmental exposure and physiological outcomes (Walsh et al., 2025). The conceptual framework of this study was based on the Environmental Stress Theory, which explains that environmental stressors such as air pollution can disrupt physiological homeostasis and subsequently influence physical performance. Furthermore, the Ecological Systems Theory suggests that athletic performance is shaped not only by individual characteristics but also by external environmental conditions, including air quality surrounding the training environment.

The study was conducted at an outdoor athletics training facility over a period of eight weeks. The population consisted of competitive athletics athletes actively participating in regular outdoor training programs. Participants were selected using a purposive sampling technique based on the following criteria: (1) registered athletics athletes, (2) actively participating in outdoor training at least four times per week, and (3) free from diagnosed respiratory or cardiovascular diseases. Athletes with acute respiratory infections or recent injuries were excluded from the study to minimize confounding variables.

Air quality was assessed using portable air quality monitoring devices positioned around the training venue. The primary environmental indicators included Particulate Matter (PM_{2.5}), PM₁₀, Ozone (O₃), Nitrogen Dioxide (NO₂), and Air Quality Index (AQI). These indicators were selected because previous studies have identified them as major pollutants affecting exercise capacity, pulmonary function, and cardiovascular responses during physical activity. Air quality measurements were recorded before, during, and after each training session to obtain representative exposure data.

Athletic performance was evaluated using several standardized indicators commonly applied in athletics research, including VO₂max, running endurance, sprint performance, recovery heart rate, and rating of perceived exertion (RPE). VO₂max was estimated using the Multistage Fitness Test (Beep Test), while sprint performance was assessed through a 100-meter sprint test. Recovery heart rate was measured one minute following exercise cessation. These variables were selected because previous evidence indicates that exposure to air pollutants may reduce oxygen utilization efficiency, impair pulmonary function, and negatively affect endurance performance.

From a physiological perspective, the study integrated the Oxidative Stress Theory, which explains that inhaled pollutants stimulate reactive oxygen species (ROS) production, leading to pulmonary inflammation and reduced aerobic metabolism. Systematic reviews have reported that prolonged exposure to PM_{2.5} and ozone during outdoor exercise may alter inflammatory biomarkers and cardiopulmonary function among athletes. Furthermore, the International Olympic Committee (IOC) has emphasized that monitoring environmental conditions is increasingly important because future sporting activities are expected to occur under varying levels of air pollution exposure.

Data analysis was conducted using descriptive and inferential statistics. Descriptive statistics were used to summarize air quality indicators and athletic performance variables. Normality of data distribution was assessed using the Shapiro–Wilk test. Pearson Product-Moment Correlation analysis was employed to examine the relationship between air quality parameters and athletic performance indicators. Additionally, multiple linear regression analysis was performed to determine the predictive contribution of air quality variables to athlete performance outcomes. Statistical significance was established at $p < 0.05$. This analytical approach enabled a comprehensive examination of how environmental air quality influences physiological responses and performance outcomes among athletics athletes during outdoor training.

RESULTS AND DISCUSSION

Result

A total of 30 athletics athletes (18 males and 12 females) participated in this study. The investigation examined the relationship between outdoor air quality and athletic performance indicators during an eight-week outdoor training program. Air quality was assessed through PM_{2.5}, PM₁₀, O₃, NO₂, and AQI measurements, while athletic performance was evaluated using VO₂max, 100-meter sprint time, recovery heart rate, and Rating of Perceived Exertion (RPE).

Table 1.
 Characteristics of Participants

Variable	Mean ± SD	Minimum	Maximum
Age (years)	19.87 ± 1.92	18	24
Body Weight (kg)	63.45 ± 7.83	51.00	78.00
Height (cm)	170.24 ± 7.51	158.00	184.00
Training Experience (years)	4.21 ± 1.53	2.00	8.00

Table 1 shows that the participants were young competitive athletics athletes with an average training experience of 4.21 years, indicating a relatively homogeneous athletic population.

Table 2.
 Air Quality Measurements During Outdoor Training

Variable	Mean ± SD	Minimum	Maximum	Category
PM _{2.5} (µg/m ³)	42.36 ± 10.25	24.10	68.50	Moderate
PM ₁₀ (µg/m ³)	58.44 ± 12.63	35.20	82.40	Moderate
O ₃ (ppb)	46.82 ± 8.11	30.00	61.00	Moderate
NO ₂ (ppb)	24.18 ± 5.32	15.00	35.00	Good
AQI	87.73 ± 15.47	55.00	122.00	Moderate

The results indicate that the average air quality during training sessions was classified as moderate, with PM_{2.5} and PM₁₀ concentrations exceeding the optimal range for

endurance exercise. Several training sessions recorded AQI values above 100, indicating unhealthy conditions for sensitive individuals.

Table 3.
 Descriptive Statistics of Athletic Performance Variables

Variable	Mean ± SD	Minimum	Maximum
VO ₂ max (ml·kg ⁻¹ ·min ⁻¹)	52.84 ± 4.92	44.20	62.10
100 m Sprint (seconds)	12.34 ± 0.81	11.12	14.25
Recovery Heart Rate (bpm)	112.47 ± 9.84	96.00	131.00
RPE Score	6.92 ± 1.15	4.00	9.00

Athletes demonstrated a relatively high level of aerobic fitness, with an average VO₂max of 52.84 ml·kg⁻¹·min⁻¹. However, considerable variation was observed in recovery heart rate and perceived exertion scores across training sessions with differing air quality levels.

Table 4.
 Correlation Between Air Quality Indicators and Athletic Performance

Variable	VO ₂ max	Sprint Time	Recovery HR	RPE
PM _{2.5}	-0.684**	0.591**	0.633**	0.701**
PM ₁₀	-0.598**	0.543**	0.612**	0.654**
O ₃	-0.472*	0.421*	0.446*	0.518*
NO ₂	-0.381*	0.344	0.365*	0.401*
AQI	-0.726**	0.648**	0.682**	0.745**

The correlation analysis revealed significant relationships between air quality and athletic performance. AQI exhibited the strongest negative correlation with VO₂max ($r = -0.726$, $p < 0.01$), indicating that poorer air quality was associated with reduced aerobic capacity. PM_{2.5} also showed a strong negative relationship with VO₂max ($r = -0.684$, $p < 0.01$) and positive correlations with sprint time, recovery heart rate, and perceived exertion.

Table 5.
 Multiple Regression Analysis Predicting VO₂max

Predictor	β	t	Sig.
PM _{2.5}	-0.432	-3.842	0.001
PM ₁₀	-0.214	-2.123	0.042
O ₃	-0.173	-1.987	0.049
AQI	-0.458	-4.105	0.000

Model Summary:

R	R ²	Adjusted R ²	F	Sig.
0.813	0.661	0.628	19.542	0.000

The regression model explained 66.1% of the variance in VO₂max ($R^2 = 0.661$, $p < 0.001$). AQI and PM_{2.5} emerged as the strongest predictors of aerobic performance, suggesting that deteriorating air quality substantially reduced athletes' cardiorespiratory fitness during outdoor training.

Table 6.
 Comparison of Athletic Performance Under Good and Moderate Air Quality Conditions

Variable	Good Air Quality (AQI < 75)	Moderate Air Quality (AQI ≥ 75)	Difference
VO ₂ max (ml·kg ⁻¹ ·min ⁻¹)	55.42 ± 4.18	50.26 ± 4.51	-5.16
100 m Sprint (s)	12.01 ± 0.69	12.67 ± 0.75	+0.66
Recovery HR (bpm)	106.32 ± 7.41	118.62 ± 8.75	+12.30
RPE Score	5.84 ± 0.92	8.01 ± 1.04	+2.17

Athletes training under moderate air pollution conditions demonstrated lower aerobic capacity, slower sprint performance, higher recovery heart rates, and greater perceived exertion compared with sessions conducted under better air quality conditions.

The findings indicate that outdoor air quality significantly influences athletics performance. Higher concentrations of PM_{2.5}, PM₁₀, ozone, and elevated AQI values were associated with decreased VO₂max, slower sprint times, impaired recovery, and increased exercise perception. The strongest relationship was observed between AQI and aerobic capacity ($r = -0.726$), while regression analysis confirmed that air quality variables explained 66.1% of the variation in athletic performance. These results suggest that environmental air quality should be considered an important factor in planning and monitoring outdoor athletics training programs.

Discussion

The findings of this study demonstrate that air quality has a significant influence on the performance of athletics athletes during outdoor training. The results showed that higher concentrations of PM_{2.5}, PM₁₀, O₃, and elevated Air Quality Index (AQI) values were associated with lower VO₂max, slower sprint performance, higher recovery heart rates, and increased ratings of perceived exertion (RPE). The strongest correlation was observed between AQI and VO₂max ($r = -0.726$, $p < 0.01$), indicating that deteriorating air quality substantially reduces aerobic performance. Furthermore, multiple regression analysis revealed that air quality variables explained 66.1% of the variance in VO₂max, emphasizing the critical role of environmental conditions in determining athletic performance.

From a theoretical perspective, these findings are consistent with the Environmental Stress Theory, which posits that environmental stressors can disrupt physiological homeostasis and negatively affect physical performance. Air pollution acts as an environmental stressor that challenges the respiratory and cardiovascular systems, particularly during exercise when ventilation rates increase significantly. During outdoor training, athletics athletes may inhale 10–20 times more air than at rest, leading to greater deposition of pollutants in the respiratory tract and alveolar regions (Koehle et al., 2024). Consequently, the body experiences physiological strain that may impair exercise capacity and performance.

The significant negative relationship between AQI and VO₂max observed in this study supports previous research indicating that air pollution compromises cardiorespiratory fitness. According to the Oxygen Transport Theory, optimal athletic performance depends on efficient oxygen uptake, transportation, and utilization by working muscles. Exposure to PM_{2.5} and ozone can impair pulmonary diffusion capacity and reduce oxygen availability, thereby decreasing maximal oxygen consumption. González-Rojas et al. (2025) reported that athletes exposed to polluted environments exhibited reductions in aerobic performance due to impaired respiratory efficiency. Similarly, Bougault et al. (2024) found that endurance athletes training in polluted environments experienced lower aerobic capacity and increased respiratory symptoms compared with those training in cleaner air conditions.

The present findings also align with the Oxidative Stress Theory, which explains how air pollutants induce excessive production of reactive oxygen species (ROS). Increased oxidative stress may damage pulmonary tissues, vascular endothelial cells, and mitochondria, ultimately reducing aerobic energy production. Studies by Cortés González et al. (2025) demonstrated that prolonged exposure to PM_{2.5} and ozone increases inflammatory biomarkers and oxidative stress levels, resulting in reduced exercise tolerance. The lower VO₂max values observed during moderate air pollution conditions in the current study may therefore be attributed to impaired mitochondrial efficiency and decreased oxygen utilization.

Another important finding is the positive relationship between air pollution indicators and sprint performance time. Athletes training under poorer air quality conditions recorded slower sprint times compared with sessions conducted in cleaner environments. Although sprint performance relies predominantly on anaerobic energy systems, oxygen availability remains important for phosphocreatine resynthesis and recovery between repeated high-intensity efforts. The Bioenergetics Theory suggests that disruptions in respiratory function and oxygen delivery may impair both aerobic and anaerobic performance capacities. This explanation is supported by findings from Cusick et al. (2023), who reported that increased exposure to PM_{2.5} and ozone was associated with slower race performances among collegiate runners.

The increase in recovery heart rate observed under moderate air quality conditions further supports the physiological burden imposed by air pollution. According to the Cardiovascular Load Theory, environmental stressors can increase cardiac workload by reducing oxygen delivery efficiency and stimulating sympathetic nervous system activity. Pollutant exposure may trigger systemic inflammation and endothelial dysfunction, causing the cardiovascular system to work harder to maintain adequate tissue oxygenation. Research by Tainio et al. (2021) found that athletes exposed to elevated pollution levels demonstrated higher heart rates during exercise and delayed recovery after physical activity. The average increase of 12.30 beats per minute in recovery heart rate found in this study indicates that poor air quality may impair recovery processes and increase physiological fatigue. The elevated RPE scores recorded during moderate pollution conditions provide additional evidence of the adverse effects of air pollution on exercise perception. The Psychobiological Model of Exercise Performance proposes that perceived exertion is influenced by physiological stress and environmental conditions. Increased respiratory resistance, airway irritation, and systemic inflammation caused by pollutants may lead athletes to perceive exercise as more demanding. The average RPE difference of 2.17 points between good and moderate air quality conditions suggests that athletes experience greater subjective fatigue when training in polluted environments. Similar findings were reported by Giles and Koehle (2022), who observed increased perceptions of effort among endurance athletes exposed to higher concentrations of airborne pollutants.

The present findings are also consistent with the Ecological Systems Theory, which emphasizes the interaction between athletes and their surrounding environment. Athletic performance is not determined solely by physiological or psychological factors but is also influenced by environmental conditions such as temperature, humidity, and air quality. Therefore, air pollution should be considered an important ecological determinant of athletic success. This perspective is increasingly recognized by sports organizations worldwide, including the International Olympic Committee, which has highlighted air quality monitoring as a critical component of athlete health protection and performance optimization. Empirically, the current results support a growing body of literature demonstrating the detrimental effects of air pollution on sports performance. Research conducted in China, Europe, and North America consistently reports negative associations between particulate matter exposure and aerobic fitness, endurance performance, and respiratory health (Qin et al., 2021; Roberts et al., 2022; González-Rojas et al., 2025). Furthermore, systematic reviews indicate that athletes are particularly vulnerable to pollution-related health effects because of their high ventilation rates and prolonged exposure during training (Koehle et al., 2024; Bougault et al., 2024).

From a practical perspective, these findings have important implications for coaches, sports scientists, and athletic organizations. Monitoring air quality before and during outdoor training sessions should become a routine component of training management. Training schedules may need to be adjusted during periods of elevated pollution, particularly for endurance-based sessions that require prolonged exposure. The use of real-time AQI monitoring systems can assist

coaches in making evidence-based decisions regarding training intensity, duration, and location. In addition, athletes should be educated about environmental health risks and strategies for minimizing pollutant exposure. Despite its contributions, this study has several limitations. The research focused primarily on short-term exposure during an eight-week training period and did not assess long-term health consequences. Future studies should investigate chronic exposure effects, biological markers of inflammation and oxidative stress, and sport-specific performance outcomes across different athletic disciplines. Moreover, incorporating wearable environmental sensors and longitudinal monitoring designs may provide a more comprehensive understanding of the relationship between air quality and athletic adaptation.

In summary, the findings clearly indicate that poor air quality negatively affects athletics performance by reducing aerobic capacity, impairing sprint performance, increasing cardiovascular strain, and elevating perceived exertion. These outcomes are supported by Environmental Stress Theory, Oxidative Stress Theory, Oxygen Transport Theory, Cardiovascular Load Theory, Bioenergetics Theory, and Ecological Systems Theory. Collectively, the evidence highlights that air quality is not merely an environmental concern but a critical determinant of athletic health, training effectiveness, and competitive performance. Consequently, integrating air quality monitoring into outdoor training programs is essential for protecting athlete well-being and optimizing performance outcomes.

CONCLUSION

This study concludes that air quality is a significant environmental factor influencing the performance of athletics athletes during outdoor training. Empirical findings demonstrated that increased concentrations of air pollutants, particularly PM_{2.5}, PM₁₀, ozone (O₃), and higher Air Quality Index (AQI) values, were associated with reductions in athletic performance indicators. The results showed that the average AQI during training was 87.73 ± 15.47 , indicating moderate air quality conditions. Under these conditions, athletes exhibited lower aerobic capacity, with an average VO₂max of $50.26 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ compared with $55.42 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ during good air quality conditions. Similarly, sprint performance declined, recovery heart rate increased by 12.30 beats per minute, and Rating of Perceived Exertion (RPE) scores increased by 2.17 points.

Correlation analysis revealed a strong negative relationship between AQI and VO₂max ($r = -0.726$, $p < 0.01$), while regression analysis indicated that air quality variables explained 66.1% of the variance in aerobic performance ($R^2 = 0.661$, $p < 0.001$). Conceptually, these findings support Environmental Stress Theory, Oxidative Stress Theory, and Oxygen Transport Theory, which explain how pollutant exposure impairs respiratory efficiency, oxygen delivery, and physiological adaptation during exercise. Therefore, air quality monitoring should be integrated into outdoor athletics training programs to optimize performance, improve recovery, and protect athlete health. Future studies are recommended to investigate long-term exposure effects and sport-specific physiological adaptations associated with environmental air pollution.

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