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Seasonal Variation in Short-Term Ambient Air Pollutants and ST-Elevation Myocardial Infarction Admissions: An Innovative Exploration of Air Pollution's Health Consequences

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Abstract: Cardiovascular diseases (CVDs) persist as a significant contributor to global morbidity and mortality despite advances in medical technology. Air pollution has emerged as a significant contemporary challenge due to increased energy consumption and rapid economic development. The study utilized multivariable Poisson regression and Distributed Lag Models (DLM) to assess the link between brief exposure to outdoor air pollutants (PM_{10}—particulate matter with a diameter $\leq$ 10 µm, NO_2—nitrogen dioxide, and O_3—ozone) and the risk of acute myocardial infarction with ST-segment elevation (STEMI) hospitalization, stratified by season. The research was conducted from January 2019 to December 2021 at the University Hospital in Timisoara, Romania, and daily records were collected for STEMI admissions, atmospheric pollutant levels, and meteorological parameters. The most pronounced impacts were observed with each 10 µg/m^3 increase at lag 07 for PM_{10} during summer, leading to a 2% increase in STEMI admissions, and for NO_2 during spring at lag 07, resulting in a 0.9% rise in CVD incidence. Men, middle-aged adults, and older adults exhibited greater susceptibility to elevated NO_2 and PM_{10} concentrations than women and younger individuals. Brief exposure to diverse air pollutants heightens the likelihood of hospitalization due to STEMI, particularly among men and adults over 45. Effective measures must be implemented to mitigate these impacts, especially for vulnerable populations.

Keywords: ST-elevation myocardial infarction; seasonal variation; ambient air pollutants; short-term exposure; acute coronary syndrome; vulnerable populations

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1. Introduction

Cardiovascular diseases, including coronary heart disease (CHD), particularly acute coronary syndromes (ACSs), persist as the predominant cause of morbidity and mortality globally despite essential advancements in medical technology and therapeutic approaches. They contribute to over 2.4 million deaths in the USA and more than 4 million deaths in Northern Asia and Europe [1,2]. ACS encompasses both ACS without ST-segment elevation (NSTE-ACS, including UA—unstable angina and NSTEMI—non-ST-segment elevation myocardial infarction) and STEMI-acute myocardial infarction with ST-segment elevation, constituting approximately 36% of all acute myocardial infarctions (AMIs) based on data from two extensive registries [3,4]. While international data indicate a declining

trend in mortality and morbidity rates among patients with CHD, Romania exhibits higher morbidity and mortality rates attributed to ACS compared to many Central and Western European countries. Nonetheless, there is evidence of a decrease in overall mortality rates among patients diagnosed with AMI in Romania, declining from 13.21% in 2004 to 8.39% in 2009, as reported by the initial Romanian registry for AMI with ST-segment elevation (RO-STEMI) [5,6].

Air pollution is a significant issue in contemporary society due to increased energy consumption and rapid economic development. In 2010, air pollution in the World Health Organization (WHO) European Region resulted in an estimated US$ 1.6 trillion in economic costs and 4.2 million premature deaths each year, with outdoor pollution being more harmful than indoor pollution [7,8].

Atmospheric pollutants, including nitrogen oxides (NOx), carbon monoxide (CO), sulfur dioxides (SO_2), ground-level ozone (O_3), and particulate matter (PM) of varying diameters (PM_{10}—particles $\leq$ 10 µm, $PM_{2.5}$—particles $\leq$ 2.5 µm, and UFP—particles $\leq$ 0.1 µm) are commonly found in both outdoor and indoor environments. Industrial, agricultural, and transportation activities significantly contribute to outdoor environmental pollution [9–11].

In recent years, numerous clinical and epidemiological studies have underscored the adverse health effects associated with both prolonged and immediate exposure to diverse environmental pollutants. Air pollution has been correlated with various cardiovascular consequences, including the exacerbation of heart failure and an increased incidence of ACS [12]. Extensive literature supports a direct correlation between both acute [13–19] and chronic [20–23] exposure to air pollutants and the occurrence of AMI. Nuvolone et al. and Belleudi et al. provided evidence indicating a heightened risk of acute coronary events associated with short-term exposure to elevated concentrations of PM_{10} [14,19]. Similarly, other studies have observed an uptick in the daily occurrences of AMI hospitalizations following acute exposure to elevated levels of NO_2 and O_3 [17,19]. Furthermore, certain research has shed light on the adverse health effects of pollution, even at concentrations lower than those recommended by the WHO, emphasizing the necessity for additional measures to improve air quality [8,21,24]. Although numerous researchers have investigated the correlation between exposure to air pollution and the risk of CHD or ACS, there has been comparatively less focus on comprehending the influence of short-term exposure to ambient air pollution on the occurrence of STEMI. This gap in the current body of literature emphasizes the need for additional research.

This study seeks to evaluate the relationship between brief exposure to outdoor air pollution and the likelihood of hospitalization due to STEMI, with a focus on seasonal variations. Furthermore, subgroup analyses were conducted considering age (young adults, middle-aged adults, older adults) and gender categories (male, female) to elucidate potential differences in the effects of air pollutants within these subpopulations. The findings of this study have the potential to inform preventive strategies aimed at reducing STEMI cases and alleviating the impact of air pollution on their occurrence.

2. Materials and Methods

2.1. Geographic Study Region

Timisoara, situated in the western region of Romania, serves as the capital of Timis County and has a population of 250,849 according to the 2021 census (https://timis.insse.ro/wp-content/uploads/2023/01/Comunicat-judet_dateprovizoriiRPL2021_ian-2023.pdf, accessed on 14 April 2024). The University Hospital for Cardiovascular Diseases in Timisoara is a referral center for cardiovascular emergencies from five counties in the southwestern region of Romania. The combined population of these counties, as reported by the National Institute of Statistics in 2023, is approximately 1,706,900 [25]. Romania exhibits a temperate-continental climate with four distinct seasons characterized by warm summers, with air temperatures exceeding 30 °C and cold winters, dropping as low as −20 °C [26].

2.2. Demographic Characteristics of Patients

This observational study included adults aged 18 years and older who were diagnosed with STEMI and admitted to the University Hospital for Cardiovascular Diseases in Timisoara, Romania, from January 2019 to December 2021. Diagnosis of STEMI was based on clinical criteria, including chest pain, biological criteria involving an increase and/or fall of high-sensitivity troponin I, and paraclinical criteria such as new persistent elevated ST-segment on the electrocardiogram and new regional wall motion abnormalities on transthoracic echocardiography. The diagnosis of ACS was confirmed by angiographic findings. The analysis encompassed clinical and paraclinical characteristics at admission, data on factors contributing to cardiovascular risk, home address, and the type of treatment received during hospitalization. Patients aged below 18, individuals diagnosed with STEMI who passed away before or shortly after hospital admission without undergoing angiographic investigation, those diagnosed with UA or NSTEMI, participants who did not provide informed consent, and individuals who did not reside in the geographical study area for a minimum of 2 weeks were excluded from the database.

All the individuals who took part in the research have given written informed consent, and the study adheres to the guidelines specified in the Declaration of Helsinki. The Scientific Research Ethics Commission of the Institute of Cardiovascular Diseases and the "Victor Babes" University of Medicine and Pharmacy in Timisoara, Romania, granted approval for the research (Approval No. 11359/16 December 2022).

2.3. Air Pollutants and Meteorological Data

The Romanian National Air Quality Monitoring Network provided information on daily concentrations of air pollutants, including NO_2, PM_{10}, and O_3. These data were collected from 24 stationary monitoring stations located near patients' residences. The study population originates from five counties within the country, each equipped with a variable number of air quality fixed monitoring stations, depending on the size of the geographical region. These data and a map displaying station locations are accessible online (https://www.calitateaer.ro, accessed on 6 April 2023). Patient residences were utilized to identify the nearest monitoring station, from which 24 h average air pollution values in micrograms per cubic meter ($\mu g/m^3$) were collected, spanning from admission day to 7 days prior to STEMI onset.

Regarding meteorological factors, daily air relative humidity (%) and temperature (°C) were obtained from the Romanian National Meteorological Association. This information was collected from the day of the event up to 7 days before the onset of ACS. All meteorological and pollution variables were collected from the southwestern region of Romania, a geographically diverse area with variations in weather parameters and pollutant concentrations, resulting in a comprehensive dataset spanning 1096 study days.

2.4. Statistical Methods

To assess data distribution, the Kolmogorov–Smirnov Test was employed. For categorical variables, percentages or numbers were used and compared using the Pearson Chi-Squared test. We expressed them as mean ± standard deviation (SD) for numerical variables and compared them using the Independent Samples *t*-test.

To investigate the correlation between brief exposure to outdoor air pollution and admissions for STEMI, a multivariable Poisson analysis using the Generalized Linear Model (GLM) and a Distributed Lag Model (DLM) was employed. A regression model was constructed, with the daily count of STEMI hospitalizations as the dependent variable. The independent variables comprised atmospheric pollutants (such as NO_2, PM_{10}, and O_3), environmental factors (RH, air temperature), and the day of the week, treated as a categorical variable, excluding legal holidays. The analysis involved increments of $\geq$10 $\mu g/m^3$ in environmental pollutants, exploring delayed associations across different single lag days covering 7 days (lag 0 to lag 7). Multi-day lags were integrated, including moving averages 0–3, 0–5, and 0–7 before the hospitalization date [27].

To evaluate potential fluctuations in pollutant effects based on seasonal variations, the data were divided into four seasons: March–May (Spring), June–August (Summer), September–November (Fall), and December–January (Winter). The study population was stratified based on age groups (20–44 years: young adults; 45–64 years: middle-aged adults; ≥65 years: older adults) and gender (male and female). Stratification by seasons was further applied within each subgroup to explore potential age- and gender-related variations in the relationship between air pollution exposure and hospitalizations for AMI. Distinct susceptibilities, risk factors, and physiological responses to environmental stressors may exist among different groups.

The study outcomes were depicted using odds ratios (OR) alongside their corresponding 95% confidence intervals (CI). Spearman's correlation analysis was employed to evaluate the relationships between daily levels of ambient air pollutants and meteorological variables. The findings were visually depicted using Excel Version 2019 to create graphical representations and statistical analyses were carried out using IBM SPSS Version 26.0 software, with a *p*-value set at less than 0.05 for analyses.

3. Results

3.1. Clinical and Demographic Features of Patients Hospitalized for ST-Segment Elevation Acute Coronary Syndrome

This study included a cohort of 2570 patients diagnosed with STEMI. Among these individuals, 72.8% (1871 patients) were male, while 27.2% (699 patients) were female, with a mean age of 61.35 ± 12.17 years. The majority of individuals fell within the age range of 45–64 years (49.3%), followed by older adults (≥65 years) at 41.6% and young adults aged 20–44 years at 9.1%.

Hypertension was the most prevalent comorbidity observed among the patients diagnosed with STEMI (61.8%). A smaller proportion of individuals had a history of diabetes (22.3%) or hypercholesterolemia (22.2%). Additionally, 45.2% of patients with AMI exhibited a single coronary artery lesion on angiography. The primary therapeutic approach for these patients was primary percutaneous coronary intervention (PCI) or balloon angioplasty (90.3%), with 23.3% receiving thrombolytic treatment prior to hospitalization. Further details regarding the clinical and laboratory features of the study group can be found in Table 1.

Table 1. Descriptive analysis of daily admissions for ST-segment elevation myocardial infarction.

	STEMI (*n* = 2570)
Gender	
male	1871 (72.80%)
female	699 (27.20%)
Age (years)	61.35 ± 12.17
Cardiovascular risk factors	
Arterial hypertension	1589 (61.82%)
Hypercholesterolemia	570 (22.18%)
Diabetes mellitus	573 (22.29%)
Types of Coronary Artery Disease	
Single-vessel lesion	1162 (45.21%)
Multi-vessel lesion	1408 (54.79%)
Type of treatment	
Fibrinolysis	677 (26.30%)

Table 1. *Cont.*

	STEMI (*n* = 2570)
Interventional approach (balloon angioplasty or PCI primary)	2320 (90.27%)
Surgical approach	48 (1.87%)
Conservative	202 (7.86%)

Data presented as mean ± SD or as number (%). STEMI: ST-segment elevation myocardial infarction; PCI: Percutaneous Coronary Intervention; SD: Standard Deviation.

In this study, the average daily admissions were determined to be 1.61 ± 0.81. The majority of days witnessed a single admission per day, constituting 69.7% of the total. Instances of two hospitalizations per day were observed on 20% of the total study days, while three or more hospitalizations per day occurred on 5% of the total days. Conversely, there were no hospitalizations on 5.3% of the observed days.

During the winter season, the prevalence of days with one hospitalization per day was highest at 71.7%, whereas in the summer, 28.2% of days saw two or more hospitalizations per day. Figure 1 displays the daily frequency of STEMI hospitalizations throughout four distinct seasons.

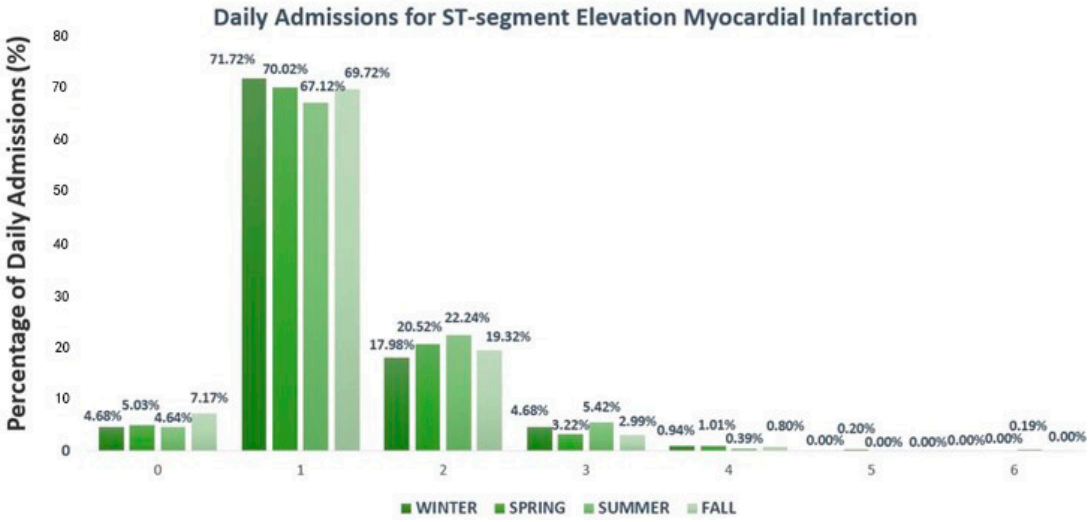

Figure 1. Daily Counts of ST-Segment Elevation Myocardial Infarction Hospitalizations Across Various Seasons. The following numerical values denote the number of daily hospitalizations: 0 means no hospitalizations, 1 means one hospitalization, 2 means two hospitalizations, 3 means three hospitalizations, 4 means four hospitalizations, 5 means five hospitalizations, and 6 means six hospitalizations per day.

3.2. Characteristics of Air Pollutants and Weather Factors

Throughout the study period, the highest average concentration of NO_2 was observed during the winter months (29.1 ± 15.5 μg/m^3), peaking in January (31.2 ± 18.0 μg/m^3). Likewise, the highest concentration of PM_{10} occurred during the fall season (24.6 ± 16.5 μg/m^3), with a peak in October (27.2 ± 20.1 μg/m^3). Spring months exhibited elevated average concentrations of O_3 (52.0 ± 17.5 μg/m^3), reaching a peak in April (61.0 ± 17.0 μg/m^3). Concurrently, the peak average air temperature registered during the summer months was 22.0 ± 3.8 °C, whereas the lowest average value during the winter season was 3.5 ± 4.4 °C. The maximum average relative humidity (RH) was noted during the winter season at 79.3 ± 13.6%, while the minimum average RH was observed during the spring months at 65.8 ± 14.6%. Further detailed information on weather and pollution variables can be found in Table 2, while variations in mean air pollutant levels across different seasons are visually depicted in Figure 2.

Table 2. Summary of Daily Air Pollutants and Weather Factors Across Four Seasons.

Study Days (n = 1096)	**Mean ± SD**	**Frequency Distribution**				
Air Pollutants (μg/m^3)		**Minimum**	**P25**	**P50**	**P75**	**Maximum**
Winter						
NO_2	29.1 ± 15.5	5.3	18.8	26.0	35.6	121.8
PM_{10}	23.4 ± 14.3	0.6	12.7	20.7	30.9	83.5
O_3	36.7 ± 19.6	5.0	21.8	33.5	47.3	127.9
Spring						
NO_2	22.2 ± 10.1	4.6	14.6	21.4	29.2	70.1
PM_{10}	17.9 ± 10.8	2.2	9.8	15.4	23.6	106.1
O_3	52.0 ± 17.5	13.2	39.1	52.3	62.0	141.7
Summer						
NO_2	20.7 ± 10.4	1.8	13.5	17.8	26.7	53.9
PM_{10}	19.0 ± 9.2	1.5	12.7	17.7	23.5	61.1
O_3	51.7 ± 15.4	11.7	40.5	51.7	61.8	95.8
Fall						
NO_2	24.5 ± 13.7	0.8	16.2	22.3	29.9	88.0
PM_{10}	24.6 ± 16.5	1.8	13.9	20.5	30.7	114.7
O_3	33.8 ± 17.2	5.0	20.4	30.7	44.7	88.8
Meteorological factors						
Winter						
Temperature (°C)	3.5 ± 4.4	−9.1	0.4	3.6	6.7	15.9
Relative Humidity (%)	79.3 ± 13.6	39.0	72.0	81.0	90.0	100.0
Spring						
Temperature (°C)	12.9 ± 5.8	−0.5	9.1	13.0	16.5	26.9
Relative Humidity (%)	65.8 ± 14.6	34.0	55.0	64.0	78.0	98.0
Summer						
Temperature (°C)	22.0 ± 3.8	8.5	19.3	22.2	24.7	30.0
Relative Humidity (%)	66.5 ± 11.8	34.0	58.0	65.0	75.0	98.0
Fall						
Temperature (°C)	12.1 ± 5.4	−1.8	7.8	12.3	16.4	24.5
Relative Humidity (%)	76.4 ± 11.7	41.0	68.0	76.0	86.0	99.0

SD: Standard Deviation; PM_{10}: particulate matter characterized by a diameter of 10 μm or less; NO_2: nitrogen dioxide; O_3: ozone.

As per WHO guidelines, pollution levels should ideally remain below certain thresholds [8]. However, concentrations of NO_2 exceeded the recommended threshold of 25 μg/m^3 on 40.2% of all observed days. Notably, the highest concentration of NO_2 was recorded during the winter season, accounting for 53% of instances. Similarly, levels of PM_{10} surpassed the designated threshold of 45 μg/m^3 on 5.1% of the observed days, with the highest concentrations observed during the fall season, reaching 9.4%. In contrast, O_3 levels exceeded 100 μg/m^3 on 0.6% of the total study days, with the highest frequency occurring during winter, accounting for 1.2% of instances.

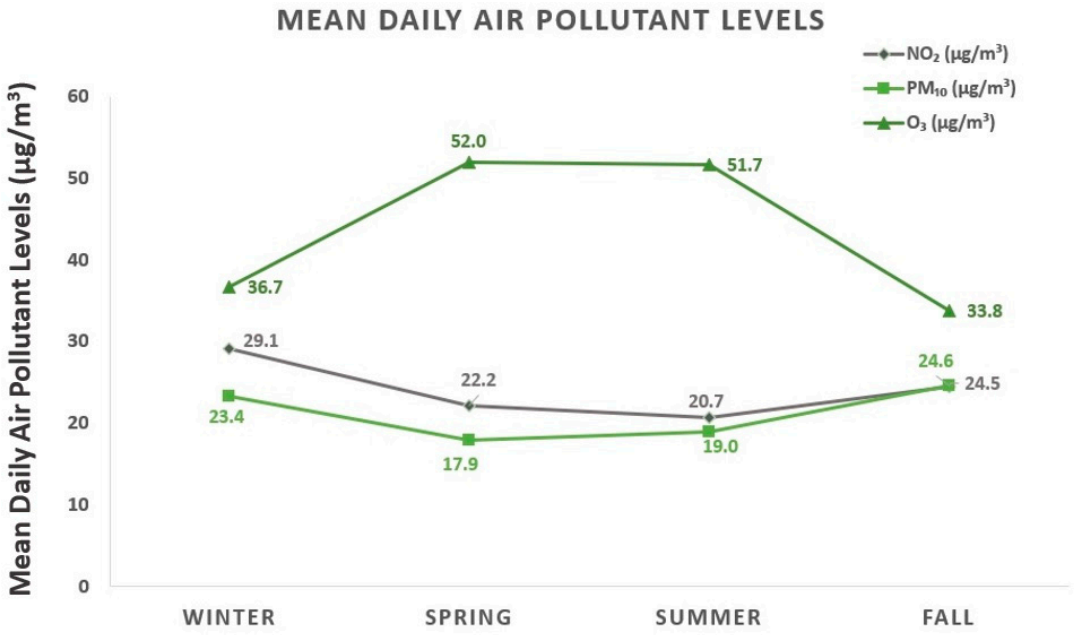

Figure 2. Dynamics of Mean Daily Air Pollutant Levels Across Four Seasons. All values are represented in μg/m^3. PM_{10}: particulate matter characterized by a diameter of 10 μm or less; NO_2: nitrogen dioxide; O_3: ozone.

We employed Spearman's correlation analysis to examine the relationships between weather parameters and daily pollutant levels in different seasons. A moderate negative correlation was observed between NO_2 and O_3, particularly during the winter and fall seasons ($r = -0.39$, $p < 0.01$). Conversely, a moderate positive correlation was noted between NO_2 and PM_{10}, notably in the fall season ($r = 0.44$, $p < 0.01$). Throughout the fall period, O_3 demonstrated a robust positive correlation with temperature ($r = 0.64$, $p < 0.01$) and a significant negative correlation with RH ($r = -0.72$, $p < 0.01$). Additionally, PM_{10} exhibited a moderate negative correlation with O_3 during the winter season ($r = -0.31$, $p < 0.01$), while in the summer months, it displayed a modest positive correlation with temperature ($r = 0.46$, $p < 0.01$) and a negative correlation with RH ($r = -0.35$, $p < 0.01$). Detailed correlations are presented in Supplementary Table S1.

3.3. Analysis of the Effects of Brief Increments in Air Pollutant Levels (≥10 μg/m^3) over Different Single and Cumulative Lag Days

We assessed the influence of atmospheric pollutants, namely NO_2, PM_{10}, and O_3, on the total number of STEMI hospitalizations. We examined the impact of brief increments in air pollutant levels (≥10 μg/m^3) on various single lag days (from lag 0 to lag 7), as well as cumulative lag days (lag 03, lag 05, and lag 07). Figure 3a–c, along with Supplementary Table S2, present detailed results of the multivariable Poisson regression analysis, illustrating the link between each 10 μg/m^3 increment in pollutants and the incidence of AMI admissions at single lag days.

The study found that short-term increases in NO_2 levels significantly influenced the daily count of STEMI hospitalizations during the spring season. This effect was observed from lag 2 to lag 3 and lag 6 to lag 7, with the most notable impact observed at lag 7, where the risk of AMI admissions increased by 0.8% (OR: 1.008, 95% CI: 1.002–1.014; $p = 0.014$). However, no such associations were identified in other seasons. Conversely, in summer, a short-term rise in PM_{10} concentration significantly affected the daily incidence of AMI cases from lag 0 to lag 7, with the strongest effect observed at lag 7 (OR: 1.017, 95% CI: 1.009–1.024; $p < 0.001$), resulting in a 1.7% increase in incidence. During the fall season, the short-term elevation in PM_{10} levels significantly increased the risk of STEMI from lag 0 to lag 2, peaking at lag 1 (OR: 1.006, 95% CI: 1.002–1.010; $p = 0.003$), leading to a 0.6% increase

in the daily number of ACS hospitalizations. No statistically significant correlations were detected for the remaining seasons based on the statistical analysis that was conducted. For O_3, no significant association was observed for any single lag day, likely due to the considerably lower concentrations of the pollutant throughout the study period.

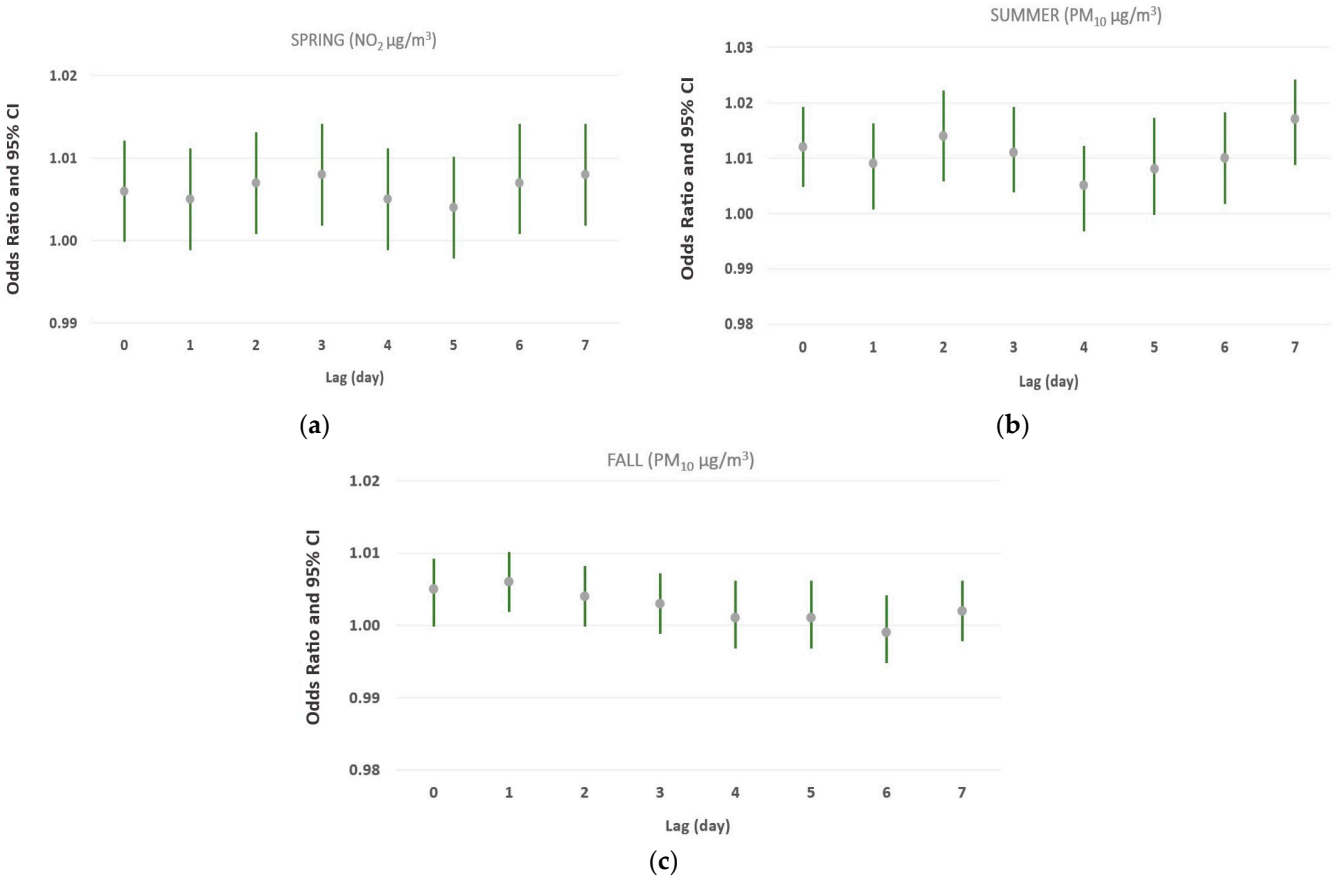

Figure 3. Multivariable Poisson Regression Analysis for Association Between 10 µg/m^3 Increase in Pollutants and Risk of STEMI Admissions at Single Lag Day. Short-term increases in NO_2 levels have a significant impact on daily hospitalizations due to STEMI during the spring season, with the greatest effect observed at lag 7 (**a**). Similarly, during the summer, a short-term rise in PM_{10} concentration notably affects the daily incidence of AMI cases, with the highest impact observed at lag 7 (**b**). In the fall season, short-term elevation in PM_{10} levels considerably increases the risk of STEMI, with the strongest effect observed at lag 1 (**c**). Graphical representation was limited to atmospheric pollutants with statistically significant associations ($p < 0.05$) observed in specific seasons. An OR > 1 indicates an elevated risk, while a value < 1 suggests a decreased risk. STEMI: ST-elevation myocardial infarction; AMI: Acute Myocardial Infarction; PM_{10}: particulate matter characterized by a diameter of 10 µm or less; NO_2: nitrogen dioxide; CI: confidence interval; OR: odds ratio.

Supplementary Table S3 and Figure 4a–c illustrate the cumulative impact of pollutants on daily STEMI admissions for every 10 µg/m^3 increase across different lag periods.

Within the total study population, significant cumulative lag effects of NO_2 were observed during spring in daily STEMI admissions for every sudden increase by at least 10 µg/m^3 at lag 03 and lag 05, with the most pronounced effect noted at lag 07, indicating a 0.9% increase in ACS hospitalizations (OR: 1.009, 95% CI: 1.001–1.016; $p = 0.019$). Additionally, during the summer season, a brief elevation in PM_{10} concentrations was associated with a rise in STEMI admissions from lag 03 to lag 07, with a more notable impact at lag 07, elevating the hospitalization risk by 2.0% (OR: 1.020, 95% CI: 1.010–1.031; $p < 0.001$). Conversely, during fall, a slightly stronger effect was observed at lag 03, resulting in a 0.6% increase in the hospi-

talization risk of AMI (OR: 1.006, 95% CI: 1.001–1.011; $p = 0.011$). No statistically significant cumulative effects were observed across seasons for the pollutant O_3.

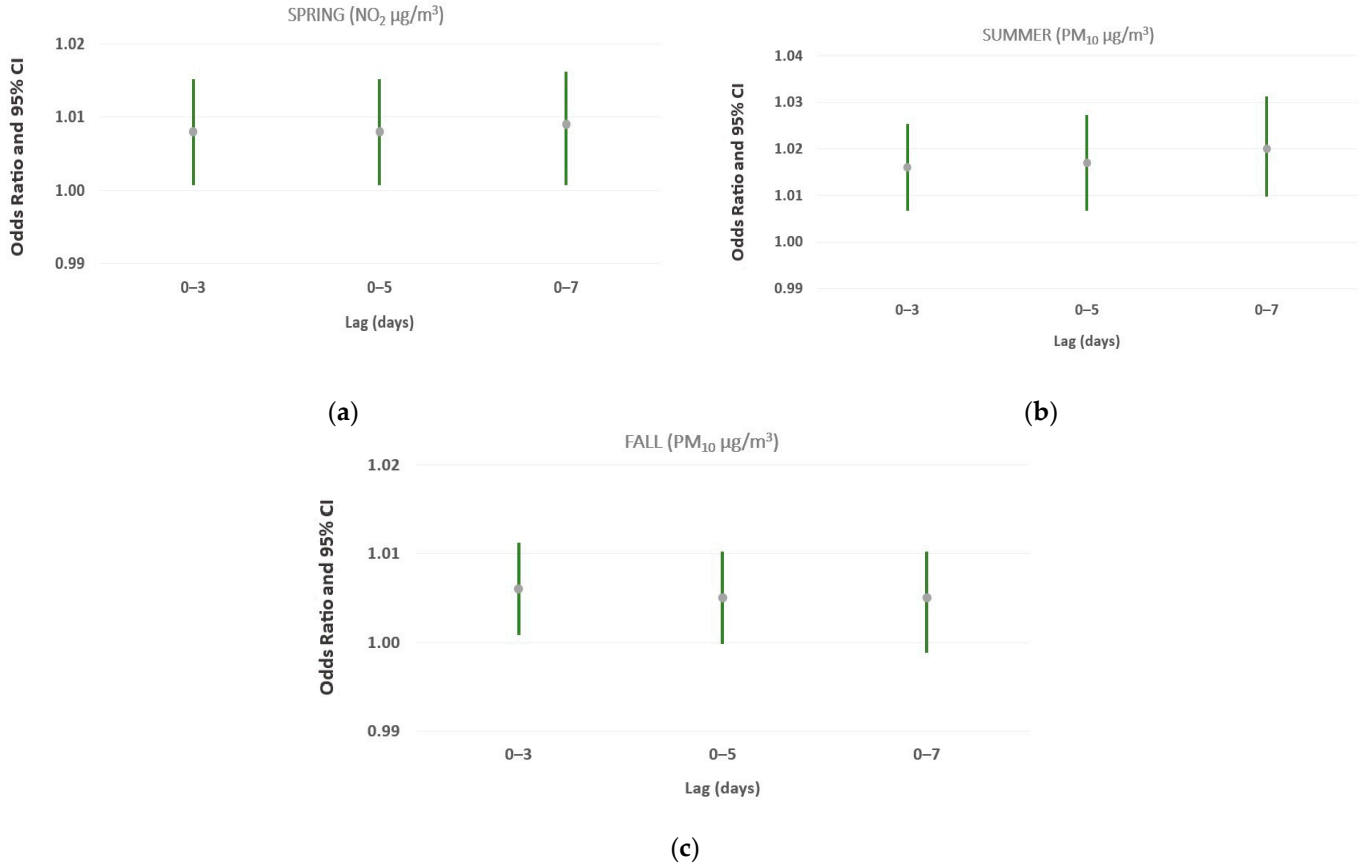

Figure 4. Multivariable Poisson Regression Analysis for Association Between 10 µg/m^3 Increase in Pollutants and Risk of STEMI Admissions at Cumulative Lag Day. The cumulative lag effects of NO_2 on daily STEMI admissions were observed during spring, with the greatest impact at lag 07 (**a**). During the summer, an increase in PM_{10} levels was associated with more hospital admissions for ACS, particularly at lag 07 (**b**). Conversely, a short-term elevation in PM10 levels significantly increased the risk of STEMI during fall, with a slightly stronger effect observed at lag 03 (**c**). Graphical representation was limited to atmospheric pollutants with statistically significant associations ($p < 0.05$) observed in specific seasons. An OR > 1 indicates an elevated risk, while a value < 1 suggests a decreased risk. STEMI: ST-elevation myocardial infarction; ACS: Acute Coronary Syndrome; PM_{10}: particulate matter characterized by a diameter of 10 µm or less; NO_2: nitrogen dioxide; CI: confidence interval; OR: odds ratio.

We performed a subgroup analysis, stratifying by gender (male and female) and age groups (young adults, middle-aged adults, and older adults), to examine the impact of pollutants across various patient categories. It was observed that O_3 did not exhibit statistical significance for the entire population, neither in the analysis considering single lag days nor in cumulative lag day assessments. Consequently, this pollutant was excluded from the subgroup analysis. Comprehensive details of the statistical analysis are provided in Table 3.

During the study, it was observed that among the male subgroup, there was an increased risk of hospitalizations due to STEMI in the spring months attributed to a short-term rise in NO_2 concentration, with the most notable impact observed at lag 07, resulting in a 1% increase in the incidence of acute coronary diseases. Conversely, no significant impact was observed in women. Additionally, during the summer season, a substantial effect of PM_{10} on the male population was noted, with the most pronounced impact occurring at

lag 07, leading to a 2.1% rise in ACS hospitalizations. However, during fall, the influence of PM10 on acute coronary events in men diminished, resulting in only a 0.6% increase in hospitalizations at lag 03.

Table 3. Multivariable Poisson Regression Analysis of Brief Increments in Air Pollutant Levels ($\geq$10 μg/m^3) and the Risk of STEMI Admission at Cumulative Lag Days Across Subgroups.

	NO_2 (μg/m^3)	**PM_{10} (μg/m^3)**
Cumulative Lag Days	**Odds Ratio (95% CI)**	**Odds Ratio (95% CI)**
Gender Subgroups		
Male		
Winter		
0–3	1.001 (0.996–1.006)	0.998 (0.991–1.004)
0–5	1.003 (0.997–1.009)	0.997 (0.990–1.004)
0–7	1.004 (0.998–1.010)	0.997 (0.989–1.004)
Spring		
0–3	1.008 (1.002–1.014) *	0.995 (0.985–1.005)
0–5	1.010 (1.003–1.017) *	0.993 (0.982–1.004)
0–7	1.010 (1.003–1.018) *	0.992 (0.980–1.004)
Summer		
0–3	1.005 (0.998–1.011)	1.017 (1.007–1.027) *
0–5	1.006 (0.998–1.014)	1.017 (1.005–1.029) *
0–7	1.007 (0.998–1.015)	1.021 (1.008–1.033) *
Fall		
0–3	1.001 (0.994–1.007)	1.006 (1.000–1.012) *
0–5	1.001 (0.994–1.008)	1.006 (0.999–1.012)
0–7	1.002 (0.994–1.009)	1.005 (0.999–1.011)
Female		
Winter		
0–3	1.004 (0.994–1.014)	0.997 (0.987–1.007)
0–5	1.003 (0.993–1.013)	0.996 (0.986–1.007)
0–7	1.003 (0.993–1.013)	0.996 (0.985–1.008)
Spring		
0–3	1.010 (0.999–1.022)	1.004 (0.988–1.020)
0–5	1.011 (0.999–1.023)	1.004 (0.987–1.021)
0–7	1.012 (0.999–1.025)	1.002 (0.984–1.019)
Summer		
0–3	1.007 (0.994–1.021)	1.016 (0.997–1.035)
0–5	1.007 (0.993–1.020)	1.016 (0.996–1.036)
0–7	1.008 (0.994–1.022)	1.020 (0.999–1.041)
Fall		
0–3	1.001 (0.991–1.012)	1.006 (0.998–1.014)
0–5	1.003 (0.992–1.013)	1.004 (0.996–1.012)
0–7	1.004 (0.993–1.014)	1.003 (0.994–1.012)

Table 3. *Cont.*

	NO_2 (μg/m^3)	PM_{10} (μg/m^3)
Cumulative Lag Days	**Odds Ratio (95% CI)**	**Odds Ratio (95% CI)**
Age Subgroups		
Young Adults (20–44 age)		
Winter		
0–3	1.009 (0.992–1.026)	0.986 (0.968–1.004)
0–5	1.009 (0.992–1.027)	0.982 (0.963–1.001)
0–7	1.009 (0.992–1.027)	0.981 (0.962–1.001)
Spring		
0–3	1.008 (0.986–1.029)	0.987 (0.945–1.031)
0–5	1.008 (0.986–1.030)	0.996 (0.953–1.041)
0–7	1.011 (0.988–1.034)	1.006 (0.959–1.056)
Summer		
0–3	1.007 (0.981–1.034)	1.027 (0.997–1.059)
0–5	1.009 (0.983–1.035)	1.027 (0.994–1.062)
0–7	1.012 (0.987–1.038)	1.032 (0.997–1.069)
Fall		
0–3	1.008 (0.987–1.029)	1.001 (0.985–1.018)
0–5	1.009 (0.986–1.032)	0.999 (0.983–1.015)
0–7	1.009 (0.986–1.033)	0.998 (0.981–1.014)
Middle-Aged Adults (45–64 age)		
Winter		
0–3	1.004 (0.997–1.011)	0.997 (0.988–1.005)
0–5	1.004 (0.996–1.011)	0.996 (0.988–1.005)
0–7	1.005 (0.997–1.013)	0.996 (0.987–1.005)
Spring		
0–3	1.009 (1.001–1.017) *	0.992 (0.980–1.004)
0–5	1.010 (1.001–1.018) *	0.993 (0.980–1.005)
0–7	1.010 (1.002–1.019) *	0.994 (0.980–1.007)
Summer		
0–3	1.003 (0.994–1.013)	1.014 (1.000–1.027) *
0–5	1.005 (0.995–1.016)	1.015 (1.000–1.030) *
0–7	1.006 (0.996–1.017)	1.020 (1.004–1.036) *
Fall		
0–3	0.998 (0.990–1.007)	1.006 (0.999–1.013)
0–5	0.998 (0.989–1.007)	1.006 (0.998–1.013)
0–7	0.999 (0.990–1.008)	1.006 (0.998–1.013)
Older Adults (≥65 age)		
Winter		
0–3	1.002 (0.994–1.009)	1.000 (0.992–1.008)
0–5	1.001 (0.994–1.009)	1.001 (0.992–1.009)
0–7	1.002 (0.994–1.009)	1.001 (0.992–1.010)

Table 3. *Cont.*

	NO_2 (μg/m^3)	PM_{10} (μg/m^3)
Cumulative Lag Days	**Odds Ratio (95% CI)**	**Odds Ratio (95% CI)**
Spring		
0–3	1.012 (1.003–1.021) *	1.004 (0.991–1.016)
0–5	1.012 (1.002–1.022) *	1.002 (0.988–1.016)
0–7	1.011 (1.001–1.022) *	0.997 (0.982–1.012)
Summer		
0–3	1.006 (0.996–1.016)	1.017 (1.004–1.030) *
0–5	1.006 (0.995–1.016)	1.016 (1.001–1.031) *
0–7	1.006 (0.996–1.017)	1.019 (1.003–1.035) *
Fall		
0–3	1.002 (0.994–1.011)	1.007 (1.000–1.014) *
0–5	1.003 (0.994–1.011)	1.006 (0.999–1.014)
0–7	1.004 (0.995–1.013)	1.005 (0.997–1.013)

* Statistically significant associations ($p < 0.05$) observed in specific seasons. An OR > 1 indicates an elevated risk, while a value < 1 suggests a decreased risk. STEMI: ST-elevation myocardial infarction; PM_{10}: particulate matter characterized by a diameter of 10 μm or less; NO_2: nitrogen dioxide; CI: confidence interval, OR: odds ratio.

In the age subgroup analysis, middle-aged and older adults demonstrated higher susceptibility to increases in NO_2 and PM_{10} levels, whereas young individuals aged 20 to 44 showed no significant impact. Among middle-aged adults, elevated pollutant concentrations had the most significant cumulative effect at lag 07 for both NO_2 in the spring and PM_{10} in the summer months. Particularly for PM_{10}, the highest impact was observed, resulting in a 2.0% increase in the risk of coronary heart disease. In older adults, exposure to NO_2 during spring showed a cumulative effect from lag 03 to lag 07, with the most significant impact observed at lag 03. Conversely, the highest impact of PM_{10} on older adults was observed during the summer, particularly at lag 07, resulting in a 1.9% increase in STEMI incidence. During the fall period at lag 03, elevated PM_{10} levels led to a cumulative risk of 0.7% for the daily number of AMI cases.

4. Discussion

This observational epidemiological investigation is the first study in our country that establishes a notable correlation between short-term exposure to elevated levels of atmospheric pollutants, particularly NO_2 and PM_{10}, and daily admissions for STEMI. Our findings reveal a considerably stronger association between the daily incidence of STEMIs and every 10 μg/m^3 increase in PM_{10} levels during the summer and fall seasons, especially at multi-day lags, compared to any single lag day. Similarly, analogous trends were identified for each 10 μg/m^3 rise in NO_2 concentrations during the spring months, indicating a heightened risk of hospitalization for AMI, particularly when analyzing cumulative lag days. Moreover, our investigation underscores that men, middle-aged adults, and older adults exhibit a heightened susceptibility to elevated pollutant levels compared to women and individuals aged 44 or younger.

Consistent with our findings, previous epidemiological research has demonstrated various effects of short-term exposure to PM_{10} on health outcomes. For instance, a study found a roughly 2.7% elevation in the mortality risk attributed to AMI linked with PM_{10} exposure, while another investigation noted an increase of about 1% in hospitalizations due to ACS following acute exposure to heightened PM_{10} levels at lag 2 [13,14]. Belleudi et al. demonstrated a 1.1% increase in the incidence rate of acute coronary events subsequent to short-term exposure to elevated concentrations of PM_{10} at lag 0, particularly prominent

during the winter season [19]. Similarly, research conducted in England and Wales found a 1.2% increase in acute coronary event risk for every 10 $\mu g/m^3$ rise in PM_{10} levels shortly after exposure [18]. A study in Belgium revealed a 2.6% increase in daily STEMI hospitalizations per 10 $\mu g/m^3$ increase in PM_{10} concentration [28]. However, some studies did not identify significant associations between ACS hospitalizations and short-term PM_{10} exposure [15,29].

Several prior investigations align with our results, demonstrating a positive correlation between brief exposure to elevated concentrations of NO_2 and the daily incidence of ACS events [14,30]. Argacha et al. also emphasized a relationship between STEMI incidence and short-term exposure to elevated NO_2 levels, with each 10 $\mu g/m^3$ increment in this pollutant leading to a 5.1% rise in hospitalizations [28]. Furthermore, another study revealed a 1.46% increase in the risk of ACS mortality due to NO_2 exposure [13]. Other researchers have demonstrated the detrimental impact of elevated concentrations of NO_2 on acute coronary events shortly after exposure. For instance, Bhaskaran et al. noted a heightened risk of AMI associated with elevated NO_2 levels at a lag of 1–6 h, while a Swedish study indicated a rise in STEMI risk at a lag of 14–24 h [18,29]. However, some studies found no association between the number of ACS hospitalizations and exposure to high levels of NO_2 [15,16].

Our study findings, consistent with existing literature, failed to establish a link between acute exposure to O_3 and the incidence of hospitalizations for cardiovascular diseases [28,29,31]. However, contrasting evidence exists, with some researchers demonstrating an elevated risk of AMI either for every 5 $\mu g/m^3$ increase in O_3 concentration at lag 0 and lag 1 or for every 10 $\mu g/m^3$ increase in O_3 level at lag 05 [16,32].

The precise mechanisms underlying the contribution of air pollution to acute coronary events remain incompletely understood. Recent clinical studies have proposed several potential pathways through which exposure to fine particles, particularly $PM_{2.5}$, may precipitate ACS. These mechanisms include the progression of coronary atherosclerotic plaques, the development of unstable plaques, and plaque rupture—observed as the culprit lesion via techniques such as computed tomographic angiography or optical coherence tomography [21,33]. Moreover, studies have suggested that exposure to heightened PM, NO_2, and O_3 concentrations may induce inflammation and oxidative stress, culminating in endothelial dysfunction and a prothrombotic state. These conditions create an environment conducive to the development of unstable atheromatous plaques characterized by elevated lipid content and substantial local inflammatory infiltration [34–38].

When examined across subgroups, our study's findings indicate that men exhibit heightened sensitivity to elevated concentrations of PM_{10} and NO_2 compared to women. This observation should be interpreted with caution, as the underrepresentation of women in our cohort (27.2%) may have affected the significance of the results rather than indicating a biological difference. The reasons underlying men's potentially increased susceptibility to air pollution in our findings remain unclear and warrant further investigation. Consistent with our results, prior epidemiological studies have also underscored men's heightened vulnerability to various air pollutants [28,39,40]. Conversely, some data have reported greater susceptibility among women following exposure to high pollutant levels [14,41].

Regarding age subgroup analysis, adults over 45 exhibited greater susceptibility to short-term exposure to PM_{10} and NO_2 than younger individuals. These findings may be elucidated by the higher frequency of exposure to pollution among middle-aged adults due to increased professional and personal activities, as they represent the predominant age group in our cohort (49.3%). In contrast, older adults, comprising the next most frequent age category in our study (41.6%), are more vulnerable to airborne pollutants due to their fragility, reduced adaptability to environmental changes, underlying comorbidities, and decreased treatment adherence. Previous research has consistently emphasized the heightened susceptibility of older adults to elevated pollution levels. Barnett et al. and Nuvolone et al. documented heightened associations between the daily count of AMI hospitalizations and $PM_{2.5}$, PM_{10}, and NO_2 among individuals aged 65 years or older [14,42]. Additionally, studies have highlighted a stronger correlation between PM concentration and nonfatal

ACS in patients aged 75 years or older [28,43]. Limited epidemiological investigations have identified significant links between the daily tally of STEMI admissions and elevated pollutant levels, particularly PM_{10}, in populations aged 54 years or younger [28].

These findings offer valuable insights into the health consequences of air pollution; however, given the limitations of our research, the small study group (2570 patients), and the restricted geographical area covered by a single university center, they should be interpreted cautiously. Our research underscores the importance of further studies, ideally conducted on a larger and more diverse cohort and in collaboration with multiple university centers, to corroborate and expand upon these findings. While our study contributes valuable data to the existing literature, it is essential to recognize that no single study can comprehensively address complex questions or drive significant policy changes on its own.

5. Conclusions

The study elucidates the intricate relationship between environmental pollutants and hospitalizations due to STEMI, with particular emphasis on seasonal variations. Our findings underscore that the association between daily admissions for ACS and air pollutants was more pronounced when considering the cumulative effect of pollutants over time rather than focusing on any single lag day. Notably, we observed that increases of 10 $\mu g/m^3$ in NO_2 levels during the spring season and PM_{10} levels during the summer and fall periods were associated with a notable rise in STEMI hospitalizations. The most substantial effects were observed at lag 07 for NO_2 during spring, lag 07 for PM_{10} during summer, and lag 03 for PM_{10} during fall.

Moreover, our study identified that men, middle-aged adults, and older adults exhibited greater susceptibility to elevated concentrations of NO_2 and PM_{10} compared to women and younger individuals. This underscores the importance of considering demographic factors in assessing vulnerability to air pollution-related health effects.

Further investigation is warranted to attain a comprehensive understanding of the intricate effects of ambient air pollution on human health and ecological systems. Effective measures aimed at mitigating these adverse impacts, particularly for more vulnerable populations, are imperative. Such initiatives should be informed by ongoing research to ensure targeted and evidence-based interventions.

Study Limitations

This study has several limitations that warrant acknowledgment. It focuses solely on investigating the correlation between outdoor air pollution and daily hospitalization rates for STEMI, thus NSTEMI, UA, or other CHD. Consequently, this limitation suggests that the findings may not comprehensively encompass the diverse range of cardiovascular conditions influenced by ambient air pollution. Furthermore, the researcher sample was drawn from a restricted geographical area covered by a single university center, and pollutant data were derived from stationary monitoring stations proximate to participants' domiciles. This approach restricts the evaluation of individual exposure to indoor air contaminants, potentially overlooking significant sources of exposure variability. Moreover, our analysis specifically focuses on the impact of pollution exposure in the 7 days preceding the event, omitting any insights into potential long-term associations. Additionally, the study does not incorporate an analysis of pollutants such as SO_2, CO, $PM_{2.5}$, and UFP due to a lack of available data during the study period. As a result of this absence, there is a possibility of underestimating the potential health effects of air pollution.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos15050590/s1, Table S1: Examination of relationships between daily air pollutant levels and weather factors using Spearman analysis; Table S2: Multivariable Poisson Regression Analysis for Association Between 10 $\mu g/m^3$ Increase in Pollutants and Risk of STEMI Admissions at Single Lag Day; Table S3: Multivariable Poisson Regression Analysis for

Association Between 10 μg/m^3 Increase in Pollutants and Risk of STEMI Admissions at Cumulative Lag Day.

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Conflicts of Interest: The authors declare no conflicts of interest.

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