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Decreased Mobility During the COVID-19 Pandemic Period Considerably Improved Air Quality in Debrecen City, Hungary

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Abstract: The effect of decreased mobility on air quality due to the COVID-19 period was analysed from 2018 to 2022 in Debrecen city, Hungary. The PM_{10} concentrations were analysed at three sampling sites. We compared PM_{10} concentrations from 2018 to 2022 during three periods: pre-pandemic, pandemic, and post-pandemic. We also studied the effect of lockdowns on the PM_{10} concentrations during the pandemic period. Over the 2018–2022 period, the concentration of PM_{10} decreased across all sites, suggesting improved air quality. Significant differences were found in PM_{10} levels among the pre-pandemic (before February of 2020), pandemic (from March of 2020 to February 2022), and post-pandemic period (after March of 2022) in the case of all stations. Significant differences were also found among years and stations during the lockdown periods. Drastically significant decreases were found only in January of 2021 in the case of all stations. Our results also demonstrated that the reduction in emissions took place simultaneously, as exceptional weather conditions such as wind direction and wind speed were observed in the year 2020, which have been highlighted by an unusually warm pre-lockdown February and springtime drought. PM_{10} levels indicated heterogeneous patterns characterized by variations including decreases, slight increases, or stability, contingent upon the specific sampling sites under consideration. These findings emphasize the complex dynamics of air pollutants and stress the necessity for ongoing monitoring and targeted interventions to alleviate detrimental effects on air quality and public health.

Keywords: decreased mobility; PM_{10}; effects of lockdown

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1. Introduction

Worldwide, the response of governments to the COVID-19 pandemic, especially the lockdown measures, led to a substantial improvement in environmental regeneration, while the pandemic and related concerns created other problems [1,2]. In order to make the best scientific use of the opportunity provided by this tragic environmental experiment, researchers around the world have conducted extensive research on the response to COVID-19 and air quality (COVID-AQ).

Overall, improved air quality during lockdowns has resulted in many averted premature deaths, emphasizing the potential for long-term air quality improvements through stringent emission control policies [3,4]. Many studies have focused on changes in air quality during lockdown periods, but most of them have been limited in scope. They have typically examined a single city [5], country [6], air pollutant [3], or specific region [7].

Public and private meetings and public and private transport were prohibited. As fewer people travelled, both the amount of fuel consumed and the level of plant activity decreased [8,9]. Minimizing the release of pollutants and various emissions caused by human activities decreases air pollution and enhances air quality [10]. Furthermore, a general increase in ozone levels has been also observed, which has now become the most prominent "quarantine effect" of NOx–O_3 chemistry [11,12]. Even if there was significantly better air quality during the lockdowns, a global measurement study has shown that that was not true worldwide. Particulate matter (PM_{10}) concentrations increased dramatically in Central and Eastern Europe during the lockdown period [13]. Air pollution remains a significant issue across Central Europe, heavily driven by emissions from transportation, industrial operations, and residential heating. Transboundary pollution from neighbouring regions also plays a critical role in exacerbating local air quality challenges. Research from Krakow, Poland, Slovakia, and Ukraine provides an essential context for understanding the regional dynamics of air pollution and the observed effects of human activity during the COVID-19 lockdown.

Salma et al. [14] studied urban air quality in Budapest, Hungary, revealing that traffic and heating emissions are dominant sources of particulate matter (PM_{10}). Similarly, studies demonstrated a sharp decline in PM_{10} levels during the lockdown, attributed to a reduction in vehicular activity and industrial processes in from Krakow, Poland [15]. Research in Slovakia highlighted that the temporary suspension of industrial operations and traffic reductions led to improved air quality, with reductions in NO_2 and PM_{10} concentrations observed across urban areas [16]. In Ukraine, significant decreases in PM_{10} and NO_2 levels during the lockdown were linked to reduced transportation and industrial activity, demonstrating the broader regional impact of reduced human activity.

Researchers mainly choose three methods for the measurement of the air pollutants: (a) before lockdown, or the pre-pandemic period [13–19]; (b) the pandemic period [20–23]; and (c) the post-pandemic period [10,24,25]. The COVID-19 period in Hungary started in early 2020 and ended in March 2022, including four lockdowns corresponding to the pandemic's four waves and two relaxation phases [26]. The lockdown periods were as follows: (i) from 11-03-2020 to 31-05-2020, (ii) from 01-11-2020 to 17-05-2021, (iii) from 01-11-2021 to 01-12-2021, and (iv) from 11-12-2021 to 06-03-2022 [26].

Our study aims to investigate the effect of COVID-19 on the air quality of 2018–2022 in Debrecen city (Hungary) during the three periods, i.e., the pre-pandemic, pandemic, and post-pandemic periods, based on the concentration of PM_{10}. We studied the effect of lockdown on the concentration of PM_{10}, and the effects of meteorological conditions (wind speed and wind direction) on the air pollutant concentration were also analysed. Data used in this study were sourced from the Hungarian Air Quality Monitoring Network, adhering to WMO guidelines, including PM10 concentrations and meteorological observations. We hypothesized that the concentration of PM_{10} was significantly lower during the pandemic and post-pandemic period than in the pre-pandemic period. Our second hypothesis was that the lockdowns had positive effects on the concentration of PM_{10}; thus, the concentration of PM_{10} was significant lower in the lockdown months than before and after the lockdown.

We also hypothesized that weather conditions, such as wind speed and wind direction, have a significant effect on the concentration of PM_{10}.

2. Materials and Methods

2.1. The Study Region and Data Source

The study region is in Debrecen, Hungary's second largest city, which is situated at an elevation of 120 m above mean sea level on the Great Hungarian Plain [27]. This region experiences typical particulate pollution, acting as a sink for aerosols carried by winds, which predominantly arrive from the northwestern direction [28]. Aerosols originating from the Sahara also occasionally impact air quality in Debrecen [29]. During winter, stagnation events are frequent due to the Carpathian Mountains' basin effect, which traps polluted air [30]. Consequently, PM_{10} concentrations frequently exceed EEA-defined standards [31]. Studies have indicated that more than 75% of Hungary's annual PM air pollution has a transboundary origin, although local sources contribute significantly, particularly during winter [32].

Debrecen city's climate is primarily dry continental, with occasional oceanic and Mediterranean influences (OMSZ). Extremely warm temperatures occurred up to the lockdown in February 2020, with a monthly mean of 5 °C, while the climatological mean was 0.5 °C for the 1981–2010 period. The low temperature was caused by cold fronts that transported abnormally dry arctic airmass (21 March, 30 March). On the 26th of March, dust from the desert region near the Aral Sea was carried by the eastern currents to the southern part of Hungary [30]. The precipitation in April was sporadic, falling on only a few days and accumulating just under 20 mm over the country and less than 5 mm in the northwestern region (the normal amount for April is 35–40 mm). During the first two weeks of the lockdown, from March 31st to April 11th, there was no rain in Hungary. Although many cold fronts brought cool temperatures in May (monthly mean temperature 14 °C, climatological mean 16 °C), they produced only a moderate amount of precipitation (20–50 mm). Between the 13th and 15th of May, dust from the Sahara descended in Hungary (based on the data of the Hungarian Meteorological Service).

Data for this study were collected between 2018 and 2022 from the Hungarian Meteorological Service. Observations were obtained from three air quality monitoring stations: Station 1 (S_1), Kalotaszeg tér, Station 2 (S_2), Debrecen Klinika Campus, and Station 3, (S_3) Hajnal Street (Figure 1).

S_1 and S_3 are located in areas with heavy traffic emissions, while S_2 represents a background location with a minimal traffic load. PM_{10} concentrations were measured using sensors such as the Grimm EDM 180 (optical), Environment SA MP101M (beta attenuation), and Thermo Scientific FH62 C14 (beta attenuation). All sensors undergo regular maintenance by the Hungarian Meteorological Service (HMS) Air Quality Reference Center, following EU directives and Hungarian norms (for further details, see https://legszennyezettseg.met.hu/levegominoseg 5 February 2023). For this study, daily PM_{10} concentrations were collected for each station from 2018 to 2022. Wind speed and direction data were collected from two meteorological stations: M_1: International Airport of Debrecen (HMS) and M_2: Macs Met (Agrometeorological Observatory of Debrecen). Anemometers at these stations are installed at a height of 10 m, following international standards, to ensure accurate and representative measurements. Wind speed and direction were recorded at 10 min intervals and averaged for daily, monthly, and annual analyses. Predominantly, winds from the northeast advance southward, affecting S_2 first, followed by S_3 and S_1. At S_2, pollutants are primarily absorbed due to the presence of vegetation, before being transported further south. Additionally, the wind sensor at M_1 is positioned at a standard height of 10 m above ground level, adhering to international guidelines for surface-level wind measurements, while the sensor height for M_2 was also confirmed to be consistent with these standards. The distances between stations and meteorological stations are shown in Table 1.

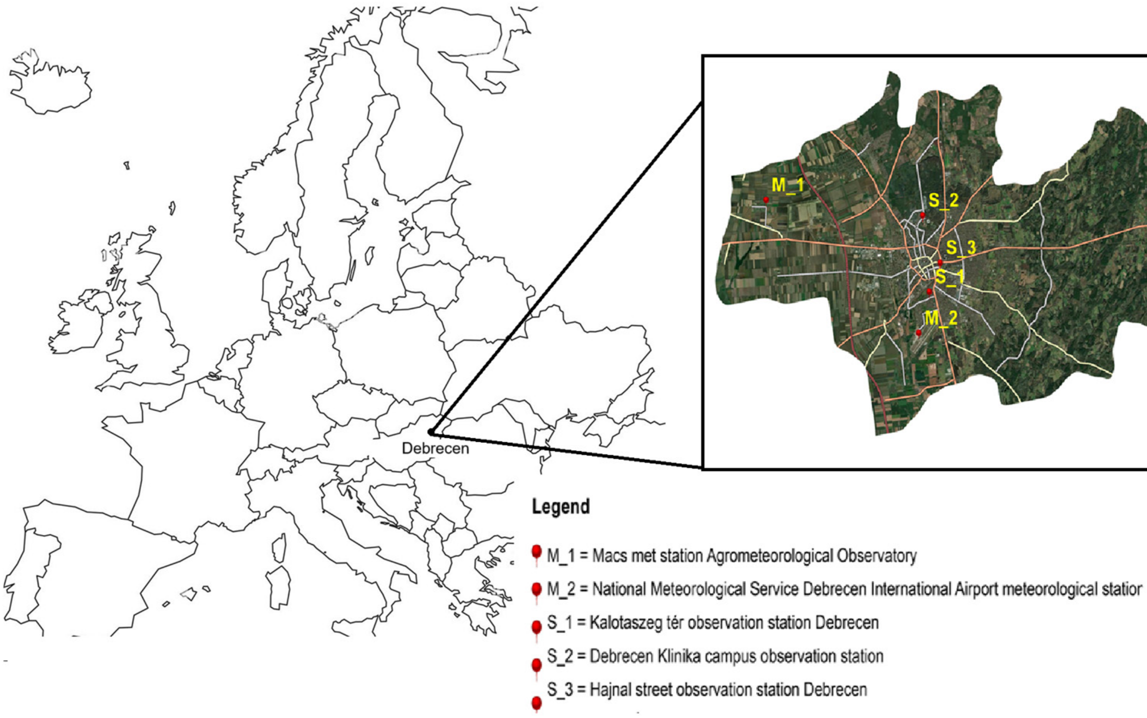

Figure 1. Location map of the study area with monitoring stations.

Table 1. Distance (in km) between stations and meteorological stations.

	Station1	**Station2**	**Station3**	**M1**	**M2**
Station1		4.85	1.99	12.89	2.78
Station2	4.85		3.24	11.07	7.51
Station3	1.99	3.24		12.88	4.76

2.2. Statistical Analysis

The daily concentrations of PM_{10} were analysed. The PM_{10} concentrations were compared among the pre-pandemic, pandemic, and post-pandemic periods with a two-way variance analysis (ANOVA), where the independent factor was the PM_{10} concentration, and the dependent factors were the stations and the studied three periods. To study the effect of lockdowns on the daily PM_{10} concentrations, we compared the years when the lockdowns were in Hungary with a two-way ANOVA. The PM_{10} concentration was the independent factor, while the stations and the studied years were the fixed factors.

3. Results

3.1. Changes in PM_{10} Concentration During the Pre-Pandemic, Pandemic, and Post-Pandemic Periods

Significant differences were found in PM_{10} concentrations among the pre-pandemic (before February of 2020), pandemic (from March of 2020 to February of 2022), and post-pandemic period (after March of 2022) in the case of all stations (Figure 2). A particularly remarkable reduction in PM_{10} concentrations was found from 2018 to 2019 (Figure 2) (Station 1: F = 231.289, $p < 0.001$; Station 2: F = 238.488, $p < 0.001$, Station 3: F = 39.293, $p < 0.001$).

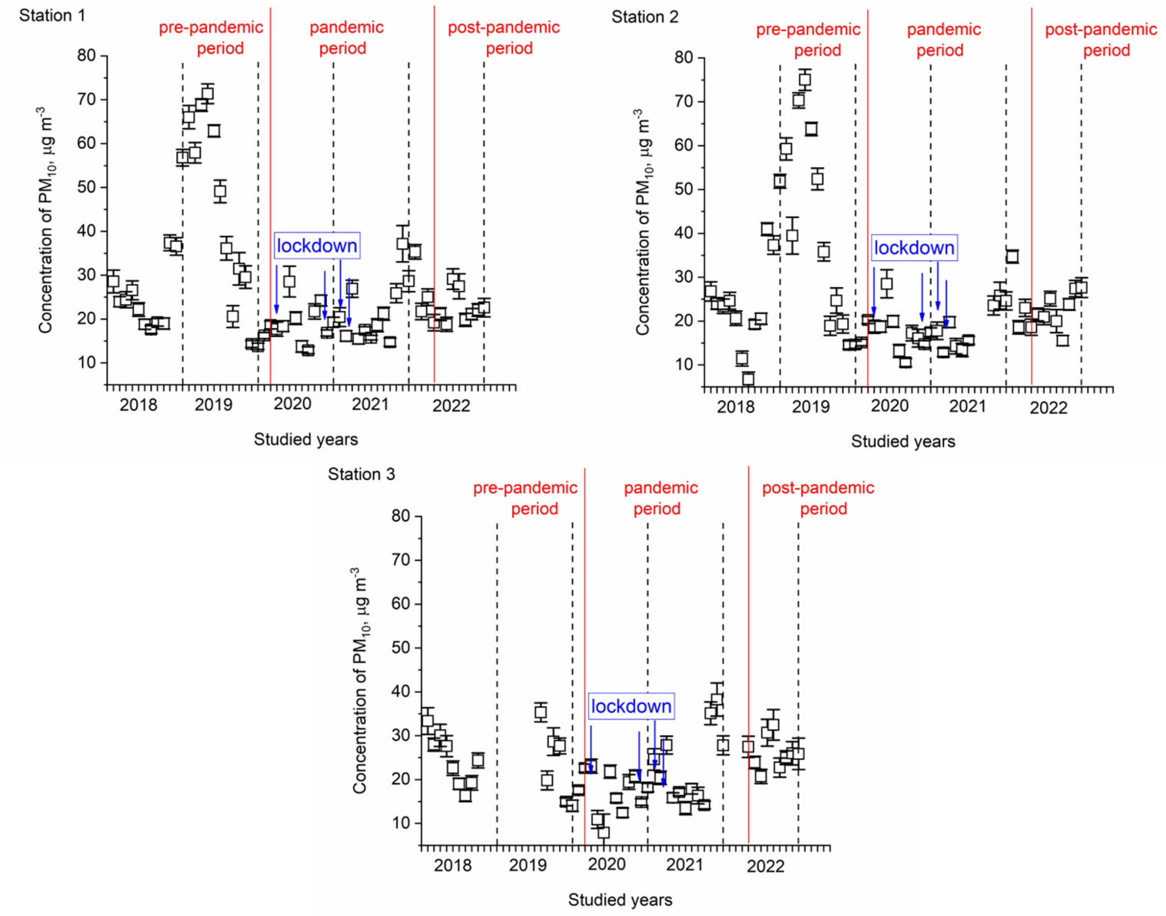

Figure 2. Daily concentration of PM_{10} (mean ± SE) during the three studied periods (pre-pandemic, pandemic, and post-pandemic) in each month. Pre-pandemic period: before March of 2020, pandemic period: March of 2020–February of 2022, post-pandemic period: after March of 2022. Notations: blue narrows indicate the time of lockdowns.

Spatially, similar PM_{10} levels were observed during the pre-pandemic period (before March of 2020) across all stations, indicating consistent pollution sources, such as vehicular and industrial emissions. Differences in PM_{10} levels were not found among stations; the average concentrations were 36 ± 2 µg/m^3 and 33 ± 2 µg/m^3 at S_1 and S_2, respectively, showing stable patterns of human activity during this period. Lower concentrations of PM_{10} were found (15 ± 6 µg/m^3) in the case of S_3.

During the pandemic period (March of 2020–February of 2022), the significant decline in PM_{10} concentrations across all stations—particularly the reduction to 21 ± 11 µg/m^3 at S_1 and 18 ± 10 µg/m^3 at S_2—aligns with the suppressed anthropogenic activities globally. The residual anomalies during this phase were minimal, indicating greater stability in air quality and supporting the interpretation that reduced emissions led to uniformly lower PM_{10} levels (Figure 2). In the case of S_3, a higher concentration was found in the pandemic period than in the pre-pandemic period based on the daily average of PM_{10} concentrations (21 ± 13 µg/m^3).

During the post-pandemic period (after March of 2022), significant differences in PM_{10} concentrations were observed between stations, such as higher levels at S_1 (18 ± 8 µg/m^3) compared to S_2 (14 ± 13 µg/m^3). The growing divergence across stations, influenced by localized factors like industrial restarts, vehicular emissions, and regional meteorological conditions, underscores the evolving nature of air quality in the post-COVID-19 recovery phase. The residual component of the decomposition further highlights episodic pollution events, such as agricultural burning, that contributed to the disparities in PM_{10} levels.

3.2. Effects of Lockdowns on the Concentration of PM_{10}

In Hungary, the lockdown periods started from March of 2020 to March of 2022 with several pauses. Significant differences were found among years and stations when we studied the same months in each year (Table 2, Supplementary Materials Table S1). Drastically significant decreases were found only in January of 2021 in the case of all stations.

Table 2. Daily PM_{10} concentration (mean ± SE) in the studied months during the lockdowns in Hungary in 2018–2022. The years when there were lockdowns in Hungary are indicated with bold. The lockdown periods were as follows: (i) from 11-03-2020 to 31-05-2020, (ii) from 01-11-2020 to 17-05-2021, (iii) from 01-11-2021 to 01-12-2021, and (iv) from 11-12-2021 to 06-03-2022. N.d. means data not detected.

Stations	Years	January	February	March	April	May	November	December
	2018	29 ± 14	24 ± 7	24 ± 10	26 ± 12	22 ± 9	36 ± 23	29 ± 13
	2019	37 ± 10	24 ± 6	23 ± 9	24 ± 11	21 ± 9	29 ± 18	25 ± 11
Station1	**2020**	36 ± 15	30 ± 8	30 ± 14	33 ± 17	23 ± 9	36 ± 20	28 ± 12
	2021	18 ± 7	38 ± 10	57 ± 11	66 ±14	58 ± 13	22 ± 10	25 ± 10
	2022	20 ± 12	19 ± 21	52 ± 9	49 ± 25	39 ± 23	16 ± 10	22 ± 12
	2018	27 ± 12	13 ± 16	n.d.	8 ± 17	n.d.	2 ± 5	3 ± 9
	2019	41 ± 8	19 ± 11	32 ± 21	24 ± 14	14 ± 4	21 ± 8	19 ± 9
Station2	**2020**	36 ± 12	19 ± 11	24 ± 16	25 ± 12	15 ± 5	22 ± 8	21 ± 10
	2021	19 ± 7	28 ± 18	29 ± 18	21 ± 8	15 ± 5	24 ± 8	19 ± 9
	2022	18 ± 11	27 ± 17	20 ± 8	14 ± 8	13 ± 4	25 ± 18	19 ± 8
	2018	33 ± 17	10 ± 22	20 ± 8	14 ± 8	11 ± 5	22 ± 12	18 ± 8
	2019	n.d.	15 ± 6	21 ± 8	15 ± 5	12 ± 6	32 ± 19	22 ± 12
Station3	**2020**	35 ± 12	15 ± 7	27 ± 11	16 ± 6	18 ± 4	25 ± 10	23 ± 12
	2021	11 ± 11	12 ± 12	20 ± 8	16 ± 10	13 ± 8	28 ± 11	25 ± 15
	2022	25 ± 14	25 ± 14	27 ± 11	25 ± 2	17 ± 5	21 ± 13	27 ± 19

The overall reduction in pollution sources due to lockdowns may have resulted in uniformly lower levels of particulate matter across the stations. While no statistically significant differences were found between S_1 and S_2 or between S_2 and S_3 (p-values of 0.461 and 0.077, respectively), a marginally significant difference emerged between S_1 and S_3 ($p = 0.077$). This suggests a potential divergence in PM_{10} levels between these two stations, likely reflecting localized factors such as variations in pollution sources, differing lockdown measures, or geographic influences on air pollutant dispersion. This marginal significance hints that as the lockdowns continued, regional factors may have started to impact air quality differently at each station, signalling a departure from the uniformity observed in previous years.

3.3. Effects of Meteorological Parameters on the Concentration of PM_{10}

The interaction between PM_{10} concentration and meteorological parameters, including wind direction and wind speed, was obtained from two meteorological stations: M_1 (National Meteorological Service) and M_2 (Macs Meteorological Station). The heat maps (Figures 3 and 4) clearly demonstrate the dependency of PM_{10} concentrations on wind parameters. During the pre-pandemic period, PM_{10} levels exhibited uniformity, with no statistically significant differences between the sites ($p > 0.05$). This consistency suggests that similar sources of pollution and regional meteorological patterns influenced air quality uniformly. However, during the post-pandemic period, localized differences emerged, as evidenced by significant variations in PM_{10} levels between S_1 and S_2 and between S_2 and S_3, reflecting the influence of localized emission sources and microclimatic factors. The integration of wind direction data with PM_{10} concentrations underscores the role of meteorology in pollutant transport and dispersion. Elevated PM_{10} concentrations were primarily associated with low wind speeds, where the reduced dispersion capacity allowed pollutants to accumulate, whereas higher wind speeds corresponded to lower concentrations, demonstrating the dispersive influence of strong winds.

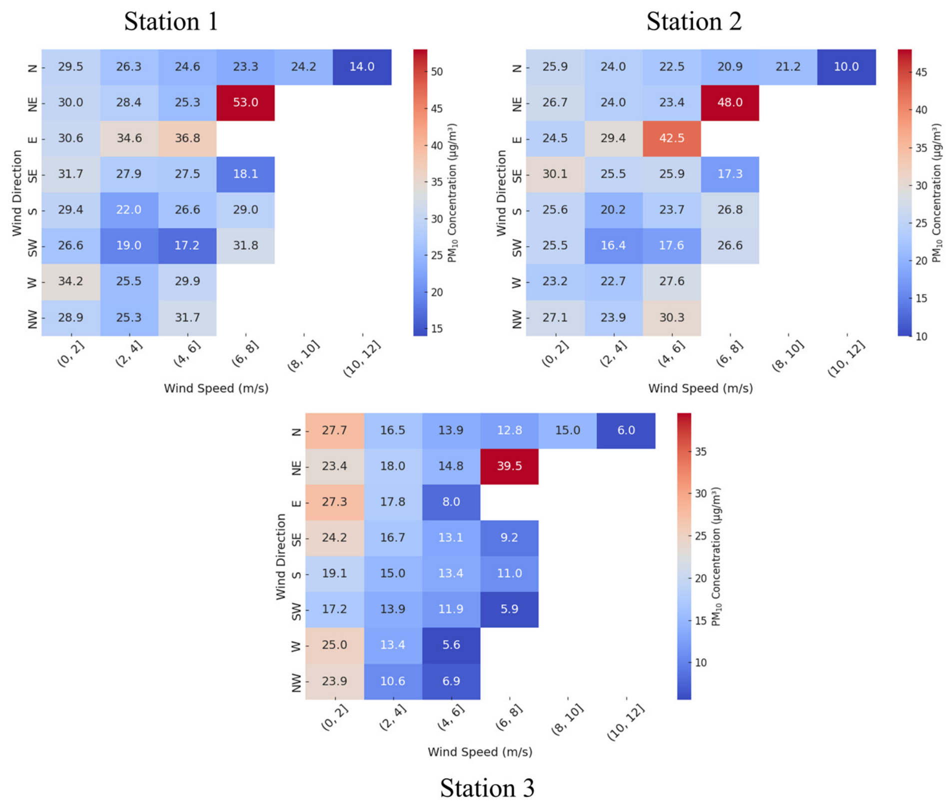

Figure 3. Heat map of PM_{10} concentrations influenced by wind speed and wind direction at the stations.

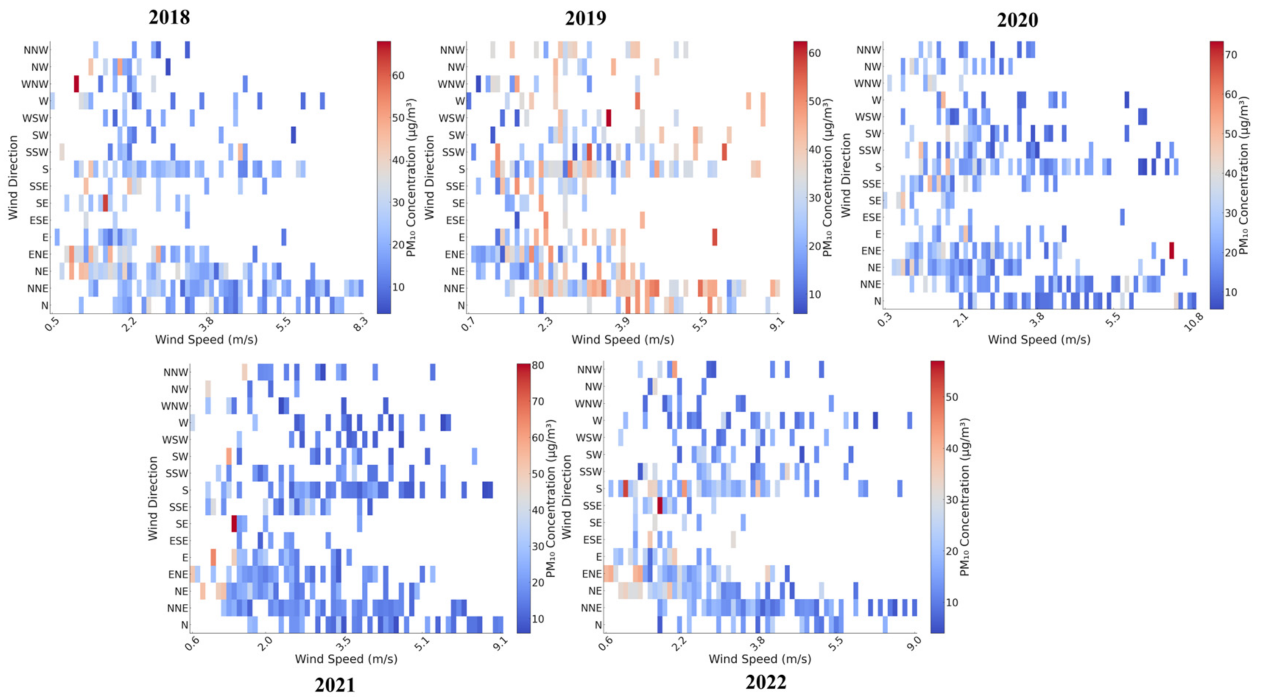

Figure 4. Heat map illustrating the relationship between PM_{10} concentration (μg/m^3), wind speed (m/s), and wind direction in the studied years. The colour gradient indicates average daily PM_{10} concentration, highlighting how pollutant concentration varies with wind speed and direction, aiding in the analysis of pollution dispersion patterns.

Moreover, the dominant wind directions (N, NW, NE) played a significant role in shaping spatial air quality variability, with specific directions aligning with elevated PM_{10} levels. This suggests the potential influence of localized sources or urban topography in those areas. While wind direction is inherently influenced by local topography and urban structures, the consistency in wind patterns observed at M_1 and M_2 indicates that the meteorological data are robust for a regional-scale analysis. Furthermore, the integration of wind direction data with PM_{10} concentrations at each station highlighted its role in shaping spatial and temporal air quality variability. Although the available meteorological data may not perfectly capture site-specific microclimatic conditions, the proximity of M_1 to the sampling sites and its compliance with international measurement standards make it a reliable source for interpreting pollutant transport and dispersion patterns in this region. The dominant wind directions are north (N), northwest (NW), and northeast (NE) (Supplementary Material Figure S1).

4. Discussion

The analysis of PM_{10} concentration across three stations from 2018 to 2022 shows that air quality remained consistent across the stations during the pre-pandemic periods in 2018 and 2019, with no significant differences, likely due to shared pollution sources and stable environmental conditions. During the pandemic period with four lockdowns in the years of 2020 and 2021, there were no significant differences across stations. A marginal difference between S_1 and S_3 in 2021 suggested that localized factors may have begun to influence air quality differently at certain stations. By 2022, in the post-pandemic period, significant differences in PM_{10} concentrations were observed, suggesting that local environmental factors and pollution sources became more prominent in shaping air quality trends. Further monitoring and investigation into the specific sources of these differences are necessary to understand the long-term impacts of post-COVID-19 recovery on air quality across these stations.

Lockdown measures have significantly improved air quality by reducing emissions of pollutants [33–37]. Diminished transportation, industrial activities, and human mobility during the lockdowns have tangibly affected air quality parameters of PM levels in Central European countries [38]. For example, Poland experienced a significant reduction in PM concentrations due to decreased traffic and industrial emissions [38]. Mobility restrictions during the pandemic have significantly reduced air pollution, with evidence indicating decreased CO emissions due to reduced outdoor mobility in various regions, including Europe [39]. Studies from Poland and Slovakia demonstrate similar findings, with notable reductions in PM_{10} concentrations during lockdowns due to decreased vehicular and industrial emissions [15,16]. These findings align with our observations in Debrecen, highlighting regional similarities. Similarly, in the UK, lockdown measures resulted in notable decreases in PM_{10} concentrations, providing associated health benefits and reducing attributable mortality [40].

Globally, COVID-19 prevention measures have led to decreases in urban mobility, electricity demand, and emissions, with the early implementation of measures in Latin American countries showing a delay in the virus's spread [41]. Lockdown measures in Europe have effectively reduced pollutant concentrations from road traffic, although the response of PM concentrations to emission reductions may vary by city [42]. While PM levels decreased across Europe due to lockdowns, there was an observed increase in ozone pollution, suggesting potential challenges in air quality management [43]. In Europe, stringent lockdown measures resulted in a significant decrease in black carbon (BC) emissions, with reductions of 20% in Italy, 40% in Germany, 34% in Spain, and 22% in France, demonstrating a direct association between the lockdowns and enhanced air quality.

The decline in air pollution, which included an average decrease of 11% in BC emissions across Europe, was unparalleled compared to corresponding periods in previous years, underscoring the immediate influence of reduced human activities on air quality [44,45] Similarly, in China, improved air quality due to mobility restrictions has mediated the association between human mobility and COVID-19 infection rates, contributing to a reduction in cases [46]. In São Paulo, Brazil, mobility restrictions improved air quality and decreased hospital admissions for respiratory illnesses, highlighting the public health benefits of reduced pollution [47]. The response of particulate matter concentrations to lockdown measures varied across different cities, suggesting complex contributions from various sources and atmospheric processes [4,34,48–50]. Similar results were also obtained in Milan [51] and in Madrid [24]. For instance, ref. [52] employed a macro-economic model in connection with Google Community Reports to determine the decline in air pollutant emissions for 129 countries resulting from limitations on individuals' mobility in six specific areas: retail and recreation, groceries and pharmacies, parks, transit stations, workplaces, and residential places. In a recent study, ref. [53] examined the extent to which various sectors in Europe have contributed to reducing primary air pollutant emissions. These sectors include energy, road traffic, and aviation.

PM concentrations showed a very heterogeneous global and regional response, ranging from a decline of 40–60% to near-stagnation to a 20–30% increase [18,21,54,55]. The period between 17 March 2020 and 11 May 2020 in France had the tightest restrictions imposed of the three in effect during 2020–2021. During the lockdown, people had only 79% of their normal mobility. Due to this, the levels of pollutants in Europe, especially in France, saw an immediate decrease. In the context of counter-COVID-19 actions, certain authors [56–59] have presented evidence of the influence of high levels of automobile traffic on air quality in Paris.

Apart from PM concentration, the Aerosol Optical Depth (AOD) in five Polish cities was measured as a proxy for aerosol concentration throughout the whole air column, with a decrease of 23% and 4% in April and May, respectively, compared to the previous year's data (2018–2019). PM_{10} levels had an increase of 8.5% and a decrease of -26.4% during the same period in 2019, while $PM_{2.5}$ levels had an increase of 8.5% and a decrease of 33.9% [16]. In the Asiatic continent, considerable reductions in PM levels were detected in China and India. At the same time, responses in Europe and the United States were often relatively small [18,20,48,55]. There is a lack of comprehensive research on the impact of air quality changes caused by both weather patterns and emission reductions during different seasons, and natural and human-induced pollution events like dust storms, wildfires, and biogenic burning. Only by employing such methods can we begin to understand the variations in pollutant concentration changes observed in different areas. Nevertheless, meteorological factors were considered to have only a secondary role in China. In contrast, the significant contribution of non-traffic emissions, such as seasonal agricultural activities and household, industrial, and power plant emissions, were cited as reasons for the lack of regional PM reduction [17,49].

5. Conclusions

This examination unveils spatial discrepancies in air pollutant concentrations among the three stations, with variations in the strength of correlations indicating diverse pollution characteristics. S_1 consistently demonstrates more robust correlations between pollutants, implying either elevated pollution levels or distinct pollution origins when contrasted with S_2 and S_3. These findings emphasize the significance of distributed monitoring networks and tailored pollution mitigation strategies to tackle localized air quality issues efficiently. We found that there was a considerable decline in the concentration of air pollutants during the lockdown period of 2020 in comparison to the baseline period of 2018–2022. For future research, it has to be noted that the severe weather that occurred in 2020 during a time of normal emissions (before the lockdown) was responsible for a more spectacular improvement in air quality than the following emission drop that occurred during adverse weather. The mean PM_{10} pollution in Debrecen during the first half of 2020 was noticeably lower than in the previous years; however, this was entirely attributable to the wintertime period that occurred before the lockdown, while elevated PM_{10} levels occurred during the curfew.

An attempt to firmly establish the aforementioned transboundary pollutant migration was made, which has been predominantly seen in the case of S_2, which is closely located to the Nagyerdő Nature Reserve Area, and which was used as a rural site for sample collection in earlier research regarding the Air Pollution Tolerant Index [60]. An investigation into adjoining S_2 revealed that, as a response to carbon sinking, a considerable portion of pollutant particles have accumulated on the sample species than had been seen at the industrial site location. According to the data, the industrial location did not exhibit any higher levels of dust pollution when compared to the rural site. The industrial site was located in the peri-urban section of the city, which meant that there was only a moderate amount of pollution coming from vehicles. Additionally, the diffusion of pollutants was not impeded by tall rows of buildings as it was in the city centre [60]. During the period of restrictions, the already atypically low levels of air pollution before the lockdown experienced an increase in the concentration of PM_{10} from the year 2018 to 2021. PM_{10} levels indicated heterogeneous patterns characterized by variations including decreases, slight increases, or stability, contingent upon the specific sampling sites under consideration. These findings emphasize the complexity of air pollutant dynamics and stress the necessity for ongoing monitoring and targeted interventions to alleviate detrimental effects on air quality and public health.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos16020197/s1, Figure S1: Windrose map depicting wind speed and direction over the study period. Table S1: Study the effect of lockdowns on the PM10 concentration with using two-way ANOVA.

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