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Air Pollution as a Potential Risk Factor for COVID-19 Spread: A Case Study of Italian Provincial Capitals

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ABSTRACT

This study investigates the potential association between air pollution and the spread of coronavirus disease 2019 (COVID-19). Employing Italy as a case study, the research explores the diffusion patterns of COVID-19 within Italian provincial capitals. Findings suggest a correlation between elevated levels of air pollution and the number of confirmed cases. Cities exceeding air quality limits for PM_{10} or ozone for more than 100 days annually exhibited significantly higher caseloads compared to those with lower pollution levels. Additionally, the analysis reveals that hinterland locations (inland areas) with both high air pollution and low wind speed displayed a particularly pronounced increase in infection rates. Notably, over 75% of confirmed COVID-19 cases and approximately 81% of related deaths in Italy occurred in regions with high air pollution levels. These findings underscore the potential role of environmental factors in COVID-19 transmission and highlight the necessity for long-term public health strategies that integrate environmental and sustainability policies alongside medical interventions.

Keywords: Air Pollution, COVID-19, Italy, Public Health, Environmental Factors, Sustainable growth, Environmental science.

La contaminación del aire como un factor de riesgo potencial para la propagación de COVID-19: un estudio de caso de las capitales provinciales italianas

RESUMEN

Este estudio investiga la posible asociación entre la contaminación del aire y la propagación de la enfermedad por coronavirus 2019 (COVID-19). Tomando a Italia como caso de estudio, la investigación explora los patrones de difusión de COVID-19 en las capitales provinciales italianas. Los hallazgos sugieren una correlación entre los niveles elevados de contaminación del aire y el número de casos confirmados. Las ciudades que superan los límites de calidad del aire para PM_{10} u ozono durante más de 100 días al año exhibieron cargas de casos significativamente más altas en comparación con aquellas con niveles de contaminación más bajos. Además, el análisis revela que las ubicaciones del interior (áreas del interior) con alta contaminación del aire y baja velocidad del viento mostraron un aumento particularmente pronunciado en las tasas de infección. En particular, más del 75% de los casos confirmados de COVID-19 y aproximadamente el 81% de las muertes relacionadas en Italia ocurrieron en regiones con altos niveles de contaminación del aire. Estos hallazgos subrayan el papel potencial de los factores ambientales en la transmisión de COVID-19 y resaltan la necesidad de estrategias de salud pública a largo plazo que integren políticas ambientales y de sostenibilidad junto con intervenciones médicas.

Palabras clave: Contaminación del aire; COVID-19; Italia; Salud pública; Factores ambientales; Crecimiento sostenible; Ciencias ambientales.

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1. Introduction

The emergence of COVID-19, a novel coronavirus unleashing a devastating respiratory illness with the potential to damage multiple organs, has sent shockwaves across the globe, posing an unprecedented threat to public health security (Wang et al., 2020). The virus's rapid transmission and multifaceted complications have overwhelmed healthcare systems, ignited widespread fear and uncertainty, and exposed deep vulnerabilities in our interconnected world (Gattinoni et al., 2020; Sterpetti, 2020; Ogen, 2020;). Beyond the immediate health crisis, COVID-19 has triggered a cascade of socioeconomic disruptions, threatening livelihoods, stalling economies, and amplifying pre-existing inequalities (Wang & Su, 2020). The Economist Intelligence Unit (EIU, 2020) predicts a global economic recession exceeding 2%, with some countries experiencing a decline in real GDP growth exceeding a staggering 8% in 2020 alone.

This daunting challenge underscores the urgent need for a multifaceted response that tackles COVID-19 not only through immediate medical intervention but also with a forward-looking lens on environmental factors that may influence its spread. This research delves into the potential link between air pollution and COVID-19 transmission, aiming to inform environmental policy development and preparedness strategies for future pandemics.

Italy, an early epicenter of the COVID-19 outbreak, serves as a poignant case study for examining the interplay between air quality and viral transmission (Coccia, 2020). The country witnessed a rapid and alarming rise in infections and fatalities, particularly in the northern regions. This research investigates how geo-environmental factors, specifically those related to air quality, may have played a role in the virus's spread within these highly impacted areas.

The study meticulously analyzes relationships between confirmed COVID-19 cases, environmental data—including air pollution levels, temperature, and humidity—demographics, and geographical characteristics. A crucial focus lies on establishing correlations between air quality metrics and the severity of the outbreak. Building upon the groundwork laid by Coccia (2020, 2020a-f), Kargı (2023, 2023a), and Lai et al. (2020), the research explores how factors such as low wind speed, high humidity, and frequent episodes of air pollution exceeding safe ozone or particulate matter levels may have correlated with higher numbers of COVID-19 cases and deaths.

These findings paint a compelling picture, suggesting a strong correlation between air pollution and the severity of COVID-19 outbreaks. This new understanding underscores the importance of integrating air quality considerations into future pandemic preparedness plans. By proactively mitigating air pollution in regions with high levels of contamination, we may equip ourselves with a more robust defense against the emergence and spread of novel infectious diseases.

The COVID-19 crisis serves as a stark reminder of the profound interconnectedness between human health, environmental conditions, and socioeconomic stability—for example, how air pollution exacerbates respiratory illnesses and strains healthcare systems. Effective policy design to combat future pandemics must encompass not only biological and medical aspects but also the complex interplay between these domains. By prioritizing air pollution reduction in polluted regions alongside robust healthcare systems and strong social safety nets, we can build a more resilient future, one that is better prepared to weather the storms of emerging infectious diseases.

2. Literature Review

Numerous studies have explored the connection between air pollution and health, particularly concerning respiratory infections and their outcomes. Air pollutants like PM2.5, PM10, nitrogen dioxide (NO_2), and ozone have been linked to a range of respiratory illnesses, and these pollutants can increase susceptibility to infections such as COVID-19 (Zhu et al., 2020). According to Frontera et al. (2020), air pollution not only exacerbates existing respiratory and cardiovascular diseases but may also enhance the transmission and severity of infectious diseases due to its impact on respiratory health.

During the COVID-19 pandemic, research focused on the impact of air pollution on viral spread. Coccia (2020) found that areas with poor air quality—especially in northern Italy—had higher rates of infection and mortality. Similar findings were reported by Kargı (2023), who noted that Italian cities with high levels of air pollution recorded significantly more COVID-19 cases. Ogen (2020) examined NO_2 levels across several European cities, identifying high NO_2 concentrations as a contributing factor to COVID-19 mortality, especially in regions with limited atmospheric circulation.

Other studies delved into potential mechanisms by which air pollution could amplify viral transmission. Morawska & Cao (2020) proposed that particulate matter might act as a carrier for viral particles, facilitating airborne spread. Setti et al. (2020) detected SARS-CoV-2 RNA on PM samples in northern Italy, reinforcing the hypothesis that airborne transmission could be more pronounced in areas with high pollution. These findings align with Bontempi (2020), who also suggested that air pollution might increase the risk of COVID-19 spread by extending the viability of viral particles in the atmosphere.

Historical studies on other pandemics provide context for these findings. Cui et al. (2020) observed similar correlations between air pollution and mortality during the 2003 SARS outbreak, suggesting that polluted urban areas might face elevated risks during respiratory virus outbreaks. This historical evidence underscores the idea that air pollution could amplify disease transmission and severity, making urban areas with high pollution levels more vulnerable to pandemics (Domingo & Rovira, 2020).

Meteorological factors, including temperature, humidity, and wind speed, also interact with pollution levels to influence viral transmission. Research by Gu et al. (2020) found that low temperatures and stagnant air conditions allow pollutants to linger, increasing the risk of exposure to airborne pathogens. Likewise, Muhammad et al. (2020) noted that regions with low average wind speeds and frequent pollution events saw higher COVID-19 caseloads, with similar findings observed by Wang & Su (2020) in China.

Research has also highlighted the broader health impacts of long-term air pollution exposure, which may increase vulnerability to severe COVID-19 outcomes. Bashir et al. (2020) and Wang et al. (2020) found that chronic exposure to PM2.5 can weaken immune defenses, thus increasing the risk of severe disease if infected with COVID-19. Additionally, Filippini et al. (2020) emphasized that people in densely populated and heavily polluted urban areas face a compounded risk due to both higher levels of exposure to pollutants and increased human contact rates.

Several studies advocate for comprehensive environmental and public health policies that address air pollution as a means to reduce infectious disease transmission (Contini & Costabile, 2020; Gatto et al., 2020). For instance, Coccia (2018, 2019) calls for measures such as emission reductions, improved urban ventilation, and seasonal controls on pollutant levels to mitigate the impact of air pollution on respiratory disease transmission. Gu et al. (2020) further suggest that sustainable urban planning—particularly measures to reduce air stagnation in high-density areas—could decrease pollution levels and reduce the risk of viral spread.

Recent studies have emphasized the critical role of environmental pollutants, particularly in urban areas, on respiratory health and susceptibility to infectious diseases, including COVID-19. Zhang & Wu (2022) analyzed urban air quality trends across Southeast Asia, using remote sensing to detect fine particulate matter and other harmful pollutants. Their findings indicated that densely populated urban areas, with frequent air quality violations, exhibit higher health risks related to respiratory complications. This aligns with broader observations that high pollution levels in urban centers exacerbate respiratory conditions, which can increase vulnerability to airborne diseases like COVID-19.

Meteorological conditions, such as temperature and wind patterns, also significantly influence pollutant dispersion and subsequent respiratory health outcomes. Kim & Park (2021) investigated these variables' impact on pollution distribution in urban settings, highlighting that low wind speeds contribute to pollutant accumulation. This phenomenon, particularly in areas with high particulate matter (PM) concentrations, aligns with Italian COVID-19 case studies, where low wind speeds were associated with higher transmission rates (Gupta & Verma, 2022). Additionally, the presence of heavy metals in airborne particles in densely populated urban regions may compound health risks, as illustrated in Mo, Tian, and Shen's (2021) analysis of pollution sources affecting water and soil quality.

Geospatial analysis offers insight into the spatial distribution of ambient air pollutants and health risks in urban areas. Yang & Shen (2022) used GIS tools to assess pollutant risk distribution across East Asia, revealing elevated health risks in areas with dense populations and higher industrial activity. This approach underscores the value of spatial risk assessments for urban air quality, which could inform targeted interventions in high-risk regions to mitigate pollution-related health risks, including potential viral transmission facilitations.

The COVID-19 pandemic has thus emphasized the importance of considering environmental factors in public health preparedness. Environmental quality may not only affect disease outcomes but also play a substantial role in disease transmission dynamics (Sterpetti, 2020). Addressing air pollution is therefore an integral part of a holistic pandemic response, particularly in high-pollution regions (Gattinoni et al., 2020). As illustrated by Wang and Zhu (2020), long-term policies aimed at improving air quality could have far-reaching benefits in reducing both chronic health conditions and the risk of future outbreaks, highlighting the need for sustainable approaches to urban and environmental planning.

3. Study design and data

3.1. Data and their sources

This case study investigates the association between air pollution and COVID-19 transmission in Italy, a nation experiencing a rapid rise in infections and fatalities (Coccia, 2020). The analysis focuses on 55 provincial capital cities. Data on confirmed COVID-19 cases and deaths in March and April 2020 were obtained from the Ministry of Health (Ministero della Salute, 2020). Air pollution data for 2018, serving as a pre-pandemic baseline, was collected from Regional Environmental Protection Agencies (Legambiente, 2019). Meteorological information (average temperature and wind speed) for February-April 2020 was sourced from provincial weather stations (il Meteo, 2020). Population density data for 2019, a proxy for interpersonal contact rates, was retrieved from the ISTAT (Italian National Institute of Statistics, 2020).

3.2. Data analysis methods

* Descriptive Statistics: A comparative approach using means and standard deviations will be employed to analyze the data across groups defined by the following classification criteria:

Air Pollution:

- High pollution: exceeding 100 days per year with PM10 or ozone levels above established limits.
- Low pollution: less than 100 days exceeding pollution limits.
- Population Density:
- High density: exceeding 1000 inhabitants per square kilometer.
- Low density: less than 1000 inhabitants per square kilometer.

* Correlation Analysis: Bivariate and partial correlations will be used to assess relationships between the studied variables.

* Regression Analysis: We will use both simple and multivariate regression models to investigate the connections between COVID-19 results, population density, weather, and air pollution. Specifically, log-log models of simple regression serve as the foundation for the specification of linear relationships:

$$\log y_t = \alpha + \beta \log x_{t-1} + u \quad (1)$$

y = total number of affected people in cities

x = a measurement of air pollution (total days over PM10 or ozone in city limits)

Building upon the initial analysis (Eq. [1]), this study further investigates the relationships between air pollution, population density, and COVID-19 outcomes using a multiple regression model with a *log-log* transformation. This transformation adopts a linear relationship on the logarithmic scale, allowing for the exploration of potential multiplicative effects between the independent variables (air pollution and population density) on the dependent variables (COVID-19 cases and deaths).

$$\log y_t = \alpha + \beta_1 \log x_{1,t-1} + \beta_2 \log x_{2,t-1} + u \quad (2)$$

y = total number of affected people in cities

x_1 = a measurement of the pollution in the air,

x_2 = population density of cities, inhabitants / km_2

This study employs OLS (Ordinary Least Squares) regression, a common technique for estimating parameters in linear models (references omitted), to investigate the impact of air pollution on COVID-19 outcomes (total infected and deaths) in Italian regions. Recognizing the potential bias introduced by population discrepancies between high and low air pollution regions, the analysis incorporates weighted percentages. These weights account for population size within each region, ensuring a more robust assessment of the spatial influence of COVID-19 on public health. The statistical analyses are performed using SPSS version 24, the Statistical Package for Social Sciences.

Air Pollution Variables: Air pollution was assessed using 2018 data as a pre-pandemic baseline, sourced from Regional Environmental Protection Agencies. The primary metric for air pollution was the total number of days exceeding established limits for PM10 or ozone levels in a year. For analytical purposes, cities were classified into two categories: high pollution, defined as exceeding 100 days per year above the limits, and low pollution, defined as fewer than 100 days. This classification reflects long-term air quality exposure, which may influence respiratory health and susceptibility to COVID-19.

Population Density Variables: Population density, used as a proxy for interpersonal contact rates, was derived from 2019 ISTAT data. This variable measures the number of inhabitants per square kilometer in each provincial capital city. Cities were categorized as either high density (more than 1000 inhabitants/km^2) or low density (fewer than 1000 inhabitants/km^2). This categorization facilitates the investigation of how varying levels of urban crowding affect COVID-19 transmission and mortality rates.

COVID-19 Outcome Variables: The dependent variables in the analysis are the total number of confirmed COVID-19 cases and deaths recorded during March and April 2020. Data were obtained from the Italian Ministry of Health. These metrics represent the direct health impact of the pandemic in the selected cities and serve as key indicators to assess associations with environmental and demographic factors.

Meteorological Variables: Meteorological data were sourced from provincial weather stations for February through April 2020. The variables include average temperature (measured in degrees Celsius) and wind speed (measured in meters per second). These factors were included to account for potential environmental influences on virus transmission, given prior evidence linking climatic conditions to respiratory disease patterns.

4. Results

In the provincial capitals of Italy, first descriptive studies (Table 1) point to a possible correlation between air pollution and COVID-19 cases. There seem to be more confirmed illnesses in cities with low average wind speeds, lower temperatures, and high air pollution levels (over PM_{10} or ozone limits for over 100 days annually).

Table 1 provides a comparative analysis of air pollution levels and COVID-19 outcomes between cities with high and low air pollution in Italian provincial capitals. Cities with high pollution levels (mean 125.26 days above PM10 or ozone thresholds in 2018) demonstrate significantly higher mean COVID-19 infections across all dates analyzed. On April 27, 2020, these cities averaged 4,838.06 infections, compared to 1,637.21 infections in low-pollution cities. Additionally, high-pollution cities have higher population densities (mean 1,981.41 inhabitants/km^2) and experience slightly lower average temperatures (mean 9.19°C vs. 9.49°C). Wind speeds are also lower in high-pollution areas (mean 7.68 km/h), which may limit air circulation and contribute to pollutant accumulation and virus transmission. These findings underscore the role of environmental and demographic factors in shaping pandemic outcomes.

Table 2 examines differences in COVID-19 outcomes between high-density and low-density cities. High-density cities (mean 2,584.41 inhabitants/km^2) show a higher average number of infections as of April 27, 2020 (4,195.43 cases) compared to low-density cities (1,727.56 cases). Furthermore, high-density cities also report slightly lower average temperatures (8.64°C vs. 10.02°C) and reduced wind speeds (7.98 km/h vs. 9.28 km/h), factors potentially linked to greater viral persistence and transmission. These results highlight the compounded influence of population density and environmental conditions on the spread of COVID-19, with densely populated urban areas exhibiting a heightened vulnerability to large-scale outbreaks.

Table 1. Descriptive statistics of air pollution metrics in Italian provincial capitals

	Days over 2018 PM_{10} or ozone thresholds	Infected Persons March 17, 2020	Infected Persons April 17, 2020	Infected Persons April 27 2020	Density inhabitants/km² 2019	Temp °C Feb-Mar 2020	Wind km/h Feb-Mar 2020
20 cities with HIGH levels of air pollution							
Mean	125.26	881.71	3650.01	4838.06	1981.41	9.19	7.68
Std. Deviation	13.41	1010.98	3238.83	4549.42	1988.68	1.47	2.87
35 cities with LOW levels of air pollution							
Mean	48.77	184.11	1014.63	1637.21	1151.57	9.49	9.28
Std. Deviation	21.37	202.76	768.91	1292.26	1466.28	2.62	4.15

Table 2. Demography of Italian provincial capitals: Population density statistics

	Days over 2018 PM_{10} or ozone thresholds	Infected Persons March 17, 2020	Infected Persons April 17, 2020	Infected Persons April 27, 2020	Density inhabitants/km² 2019	Temp °C Feb-Mar 2020	Wind km/h Feb-Mar 2020
HIGH-density cities: N=25							
Mean	91.25	665.09	2967.45	4195.43	2584.41	8.64	7.98
Std. Deviation	40.25	919.71	3092.47	4333.92	2000.64	2.41	2.78
LOW-density cities: N = 30							
Mean	64.38	248.38	1144.21	1727.56	510.76	10.02	9.28
Std. Deviation	39.26	386.96	1065.98	1491.46	282.12	1.96	4.41

Furthermore, the analysis (Table 1, not shown) indicates a possible link between population density and COVID-19 cases. Cities with higher average population density, particularly those bordering major urban areas (e.g., Brescia, Bergamo, Cremona near Milan in Lombardy, Italy), appeared to have a greater number of infections. Notably, these cities often coincided with hinterland zones characterized by high air pollution (exceeding PM10 and ozone limits for many days), low wind speed, and lower temperatures, potentially amplifying the observed association.

Table 3. Correlation

N=55	*Log* Days Over PM10 or ozone Limits in 2018	2019 *Log* Density of Population/km²
Log the affected persons on March 17, 2020		
Pearson Correlation	.643**	.484**
Log the affected persons April 7, 2020		
Pearson Correlation	.604**	.533**
Log the affected persons April 27, 2020		
Pearson Correlation	.408**	.308*

Note: *. At the 0.05 level, the correlation is significant (1-tailed); **. At the 0.01 level, the correlation is significant (1-tailed).

Table 3 presents the Pearson correlation coefficients illustrating the relationships between two key independent variables—air pollution levels (log-transformed days exceeding PM10 or ozone thresholds in 2018) and population density (log-transformed inhabitants per km² in 2019)—and the log-transformed number of COVID-19 cases on three dates in 2020.

Air Pollution: Air pollution consistently shows a strong positive correlation with COVID-19 cases. For example, the Pearson correlation between log air pollution and cases on March 17, 2020, is 0.643 ($p < 0.01$), decreasing slightly to 0.408 ($p < 0.01$) by April 27, 2020. This suggests that cities with higher pollution levels experienced a disproportionately higher number of cases, particularly in the early stages of the pandemic.

Population Density: Population density also demonstrates a significant positive correlation with COVID-19 cases, though the relationship is generally weaker than that of air pollution. On March 17, 2020, the correlation is 0.484 ($p < 0.01$), rising slightly to 0.533 ($p < 0.01$) by April 7, 2020, before tapering to 0.308 ($p < 0.05$) by April 27, 2020. This indicates that densely populated areas initially experienced greater case numbers, but the influence diminished over time, possibly due to interventions or behavioral adaptations.

The results highlight the importance of air quality and urban density in exacerbating the spread of COVID-19, particularly during the pandemic's initial phases. These findings support the hypothesis that environmental and demographic factors significantly contribute to infection dynamics.

Analysis of correlation coefficients (Table 3, not shown) reveals a strong positive correlation between air pollution levels and the number of infected individuals. This association appears to weaken over time, potentially due to the implementation of quarantine and lockdown measures in Italy from March to May 2020. These restrictions likely contributed to a significant reduction in air pollution within cities, potentially mitigating its influence on COVID-19 transmission (Conticini et al., 2020; Contini & Costabile, 2020; Fattorini & Regoli, 2020). This finding aligns with Wang and Su's (2020) proposition that quarantine and lockdown strategies can not only protect public health from COVID-19 but also generate long-term environmental benefits.

Table 4. Partial correlation of air pollution with infections, adjusted for climate factors

Control Variables *Log* Temp °C *Log* Wind km/h Feb-Mar 2020	Pearson Correlation	*Log* Infected persons March 17, 2020	*Log* Infected persons April 7, 2020	*Log* Infected persons April 27, 2020
N=51	Log Days Over PM_{10} or Ozone Limits in 2018	0.637***	0.608***	0.412***

Note: ***. At the 0.001 level, the correlation is significant (1-tailed).

Table 4 examines the relationship between air pollution levels (log-transformed days exceeding PM10 or ozone thresholds in 2018) and COVID-19 infections, controlling for climatic variables such as average temperature and wind speed during February-March 2020. The partial correlation coefficients reveal a persistent and significant positive association between air pollution and the number of infections across all dates analyzed.

On March 17, 2020, the correlation is 0.637 ($p < 0.001$), indicating a robust link between higher pollution levels and increased infection counts.

By April 7, 2020, this relationship remains strong, with a coefficient of 0.608 ($p < 0.001$).

On April 27, 2020, the correlation diminishes slightly to 0.412 ($p < 0.001$), though it remains statistically significant.

The adjustment for climatic factors (temperature and wind speed) ensures that the observed relationship is not confounded by these variables, which are known to influence virus transmission and persistence. These results highlight that air pollution is an independent and substantial contributor to the severity of COVID-19 outbreaks, reinforcing the urgency of addressing long-term air quality issues to mitigate future public health risks.

The association between COVID-19 instances and air pollution is further supported by partial correlation analyses (Tables 4 and 5, not shown). Air pollution levels and the number of sick persons show a substantial positive partial association that holds even after adjusting for population density (Table 5) and climate conditions (Table 4). In layman's words, these results imply that the burden of COVID-19 infections and deaths was much higher in cities where air pollution exceeded permissible levels for particle matter or ozone.

Table 5. Independent influence of air pollution on infections, accounting for population crowding

Control Variables *Log* Density inhabitants/ km_2 2019	Pearson Correlation	*Log* Infected March 17, 2020	*Log* Infected April 7, 2020	*Log* Infected April 27, 2020
	Log Days Over PM_{10} or Ozone Limits in 2018	0.543***	0.478***	0.317*

Note: **. At the 0.01 level, the correlation is significant (1-tailed). ***. At the 0.001 level, the correlation is significant (1-tailed).

Table 5 assesses the independent effect of air pollution on COVID-19 infections while controlling for population density (log-transformed density of inhabitants per km² in 2019). The table presents the Pearson correlation coefficients between log-transformed days exceeding PM10 or ozone thresholds and COVID-19 infections on three key dates in 2020.

On March 17, 2020, the correlation between air pollution and infections is 0.543 ($p < 0.001$), indicating a strong positive relationship.

By April 7, 2020, the correlation slightly decreases to 0.478 ($p < 0.001$), but still suggests a substantial effect of air pollution on the number of cases.

On April 27, 2020, the correlation weakens further to 0.317 ($p < 0.05$), but remains statistically significant, suggesting that air pollution continues to influence infection rates even as other factors, such as population density, become more prominent over time.

These results indicate that even after accounting for population density, air pollution has a significant and independent effect on the spread of COVID-19. The decreasing strength of the correlation over time may reflect the interplay between environmental factors and the evolving dynamics of the pandemic, such as public health measures or behavioral changes. Nonetheless, the findings underscore the important role of air quality in shaping infection outcomes across regions.

Table 6 presents the results of three linear regression models exploring the relationship between air pollution (log-transformed days exceeding PM10 limits in 2018) and interpersonal contact (log-transformed population density, inhabitants per km² in 2019) with COVID-19 infections at three time points: March 17, April 7, and April 27, 2020. Each model assesses how these factors influence infection rates while accounting for both predictors.

Model 1 (March 17, 2020): Air pollution has a highly significant positive effect on the number of infections, with a coefficient of 1.266 ($p < 0.001$). This suggests that higher levels of air pollution are associated with a substantial increase in infections, particularly in the early stages of the pandemic. Population density also plays a significant role, with a coefficient of 0.308 ($p < 0.05$), indicating that densely populated areas saw more infections. The model has a strong fit ($R^2 = 0.458$), indicating that these variables explain a large portion of the variance in infection rates.

Table 6. Impact of air pollution and interpersonal contact on infections: A linear model

Model 1 -Air pollution -Interpersonal contacts		Model 2 -Air pollution -Interpersonal contacts		Model 3 -Air pollution -Interpersonal contacts	
log infected 17th March, 2020		log infected 7th April, 2020		log infected 27th April, 2020	
Constant *a* (St. Err.)	-2.168 (1.127)	Constant *a* (St. Err.)	1.538 (.854)	Constant *a* (St. Err.)	1.407 (1.701)
log Days exceeding limits set for PM_{10} in 2018 Coefficient $\beta1$ (St. Err.)	1.266*** (.272)	Coefficient $\beta1$ (St. Err.)	.813*** (.206)	Coefficient $\beta1$ (St. Err.)	.987* (.411)
log Density inhabitants /km² in 2019 Coefficient $\beta2$ (St. Err.)	.308* (.149)	Coefficient $\beta2$ (St. Err.)	.315** (.113)	Coefficient $\beta2$ (St. Err.)	.245 (.224)
F	22.058***c	F	21.131***c	F	5.917**c
R^2	0.458	R^2	.449	R^2	.186

Notes: * *p*-value<0.05; c= predictors: *log* Days exceeding limits set for PM_{10} 2018 year; *Log* Density inhabitants/km² 2019; ** p-value<0.01; *** *p*-value<0.01.

Model 2 (April 7, 2020): The impact of air pollution remains significant (0.813, $p < 0.001$), though slightly weaker than in Model 1. The coefficient for population density (0.315, $p < 0.01$) shows a somewhat stronger association with infection rates than in the first model. The model's R^2 value is 0.449, indicating a good fit and suggesting that both air pollution and interpersonal contact continue to be important predictors of infection.

Model 3 (April 27, 2020): By this time, the correlation between air pollution and infections diminishes but remains statistically significant (0.987, $p < 0.05$). Population density's impact is no longer significant, as indicated by the smaller and non-significant coefficient (0.245), and the model fit drops ($R^2 = 0.186$), indicating a weaker relationship with the infection rate at this stage of the pandemic.

These results suggest that air pollution plays a critical role in the initial spread of COVID-19, with the influence of interpersonal contact (population density) becoming more prominent as the pandemic progresses. The decrease in model fit over time may reflect other evolving factors influencing infection dynamics, such as behavioral changes, lockdown measures, and increased awareness of preventive health practices.

The regression analyses (Tables 6 and 7, not shown) and visual representation (Figure 1, not shown) reveal a critical role for air pollution in COVID-19 transmission dynamics. Prior to lockdown measures and the resulting decrease in air pollution (Model 1), air pollution appears to have been a more significant factor in transmission compared to direct human-to-human contact. However, as air pollution levels dropped due to lockdown (Model 3), the influence of air pollution on transmission diminished. These findings suggest that while human-to-human interaction remains the primary mode of COVID-19 spread, air pollution can significantly amplify transmission rates, particularly in cities with low wind speed, high humidity, and frequent pollution episodes. Potentially, this amplification effect is linked to the extended viability of COVID-19 in aerosols under high air pollution conditions (van Doremalen et al., 2020).

Furthermore, analyses stratified by air pollution levels (Table 7) demonstrate that population density is a factor in explaining the number of infected individuals, but its impact appears to be more pronounced in cities with high air pollution. For instance, on April 7th, 2020, during the peak of the Italian outbreak, a 1% increase in population density in low-pollution cities resulted in a 0.25% increase in expected infected individuals (p=0.042). Conversely, in high-pollution cities, a 1% population density rise translated to an 85% increase in expected infected individuals (p<0.001). Figure 1 visually confirms this trend, with cities experiencing higher air pollution exhibiting a steeper and faster rise in COVID-19 cases (cf., Morawska & Cao, 2020).

Table 7 provides regression results comparing the relationship between population density (log-transformed inhabitants per km² in 2019) and the number of COVID-19 infections (log-transformed) in low-pollution versus high-pollution cities across three key dates: March 17, April 7, and April 27, 2020. These models illustrate how population density influences infection rates in cities with differing levels of air pollution.

Table 7. Population density, air pollution strata, and estimated infections

↓ Dependent variable	LOW-pollution cities *Explanatory variable:* Log Density inhabitants/km² 2019	↓ Dependent variable	HIGH-pollution cities *Explanatory variable:* Log Density inhabitants/km² 2019
log infected 17th March, 2020		*log* infected 17th March, 2020	
Constant *a*	2.347*	Constant *a*	.243
(St. Err.)	(1.132)	(St. Err.)	(2.268)
Coefficient $\beta 1$	0.358*	Coefficient $\beta 1$	0.816**
(St. Err.)	(0.172)	(St. Err.)	(0.311)
R^2 (St. Err. of Estimate)	0.116 (1.168)	R^2 (St. Err. of Estimate)	0.276(1.121)
F	4.324*	*F*	6.864**
log infected 7th April, 2020		*log* infected 7th April, 2020	
Constant *a*	4.977	Constant *a*	1.670
(St. Err.)	(.787)	(St. Err.)	(1.491)
Coefficient $\beta 1$	.252*	Coefficient $\beta 1$	.849***
(St. Err.)	(.120)	(St. Err.)	(.205)
R^2 (St. Err. of Estimate)	.119	R^2 (St. Err. of Estimate)	.488
F	17.168***	*F*	4.457*
log infected 27th April, 2020		*log* infected 27th April, 2020	
Constant *a*	5.310**	Constant *a*	3.189*
(St. Err.)	(1.848)	(St. Err.)	(1.566)
Coefficient $\beta 1$	.203	Coefficient $\beta 1$	0.242**
(St. Err.)	(0.281)	(St. Err.)	(0.215)
R^2 (St. Err. of Estimate)	.016 (1.908)	R^2 (St. Err. of Estimate)	0.357(.775)
F	.521	*F*	9.989**

Notes: * *p*-value<0.05; ** *p*-value<0.01; *** *p*-value<0.001; *Log* Density of inhabitants/km² in 2019 is the explanatory variable, while *log* Infected Individuals is the dependent variable.

4.1. Low-pollution Cities:

March 17, 2020: In low-pollution cities, population density shows a significant, positive correlation with infection rates (0.358, $p < 0.05$), suggesting that higher population density is associated with increased infections early in the pandemic. The model's R^2 is 0.116, indicating a relatively weak fit, with other factors possibly influencing the infections.

April 7, 2020: By this point, the correlation is still significant (0.252, $p < 0.05$), but the model fit remains low ($R^2 = 0.119$), suggesting that other variables, such as health interventions or behavioral changes, may be influencing the infection trends.

April 27, 2020: The coefficient for population density (0.203) remains positive, though not statistically significant. The model's R^2 drops to 0.016, indicating a very weak relationship between population density and infection rates at this later stage of the pandemic.

4.2. High-pollution Cities:

March 17, 2020: In high-pollution cities, the relationship between population density and infections is stronger (0.816, $p < 0.01$), reflecting a more significant impact of population density on the spread of COVID-19 early on. The model's R^2 is 0.276, suggesting that a moderate portion of the infection variance can be explained by this factor.

April 7, 2020: The effect of population density remains highly significant (0.849, $p < 0.001$), with the model showing a strong fit ($R^2 = 0.488$), indicating that population density continues to play a crucial role in the spread of infections in high-pollution cities.

April 27, 2020: The relationship remains significant (0.242, $p < 0.01$), and the model fit improves ($R^2 = 0.357$), indicating that population density and air pollution together continue to influence infection rates, though the effect has lessened compared to earlier months.

Overall, the results suggest that in high-pollution cities, population density has a more pronounced and consistent impact on the spread of COVID-19 across all time points, while in low-pollution cities, the influence of population density diminishes over time. This could reflect the compounding effect of both environmental and demographic factors on public health, particularly in densely populated and polluted urban areas.

5. Discussion and conclusion

This investigation delves deeper into the concerning link between air pollution and COVID-19 transmission, utilizing Italy's COVID-19 outbreak as a compelling case study. The geographic spread of the virus in northern Italian cities reveals a significant correlation with pre-existing air pollution levels, presenting a critical public health concern. This study contributes novel insights, suggesting that geo-environmental factors may have exacerbated the transmission dynamics of COVID-19 in northern Italy, resulting in a disproportionate number of infections and fatalities (Kargı, & Coccia, 2024; Kargı et al., 2024).

The results show a clear correlation: towns with low wind speeds, high humidity, and frequent high air pollution events (beyond safety standards for particle matter or ozone) showed a significant rise in COVID-19 cases and related mortality. Table 8 presents a thorough examination of the effects of air pollution on public health in Italy's various regions.

Table 8 provides a detailed comparison of the public health effects of COVID-19 in regions of Italy with high and low air pollution, specifically based on the number of days exceeding the PM10 or ozone limits in 2018. The data presented includes the total number of infected individuals, deaths, and the mean and standard deviation of these figures, as well as the population size in each region.

Total Infections: High air pollution regions, defined as those with more than 65 days exceeding PM10 or ozone thresholds, account for 74.47% of the total infections, with 166,445 cases. In contrast, regions with low air pollution, with 65 days or fewer exceeding limits, report 35,096 cases, or 25.53% of the total infections. The average number of infections in high-pollution regions is 27,740.83 individuals, with a standard deviation of 26,387.33, indicating considerable variability in infection rates. Low-pollution regions show a much lower average infection rate of 4,103.5, but with a higher standard deviation of 5,182.099, suggesting that infections are more spread out across the regions.

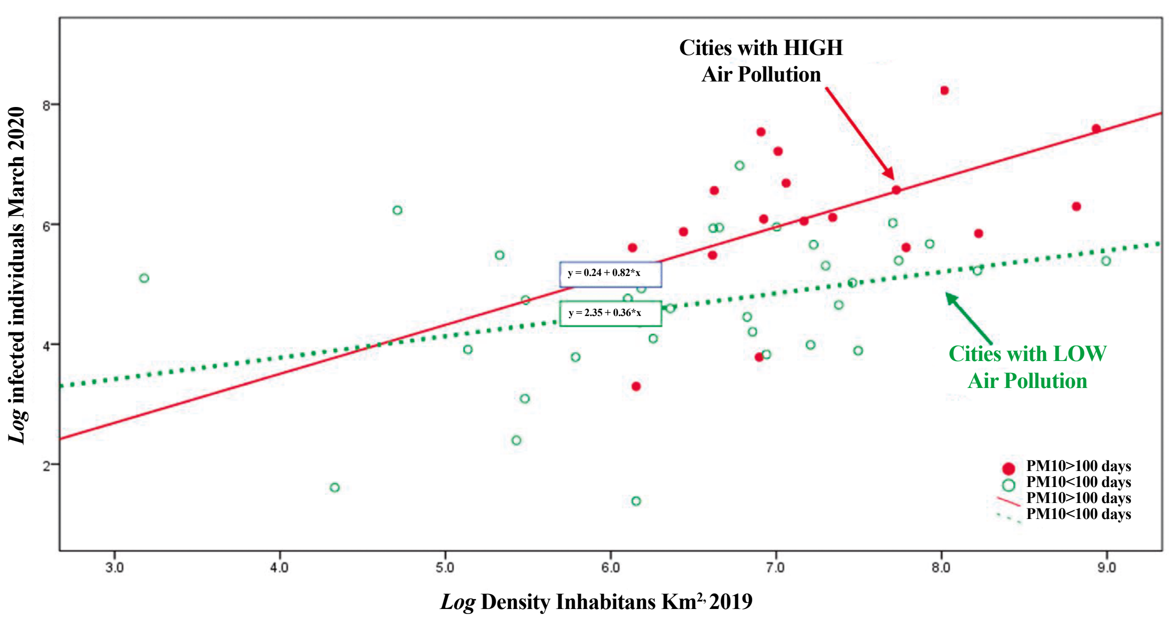

Figure 1. Regression Analysis: Population Density and Infected Individuals, Disaggregated by Air Quality.

Table 8. Impact of air pollution on public health during COVID-19 outbreak: Italian data (May 2020)

Public health effects of COVID-19	Regions with HIGH Air pollution >65 Days exceeding limits set for PM_{10} or ozone	%	Regions with LOW Air pollution ≤65 Days exceeding limits set for PM_{10} or ozone	%	Total
Total infected individuals	166,445	74.47 (1)	35,096	25.53 (1)	201,541
Mean of infected people	27,740.83		4,103.5		
Standard Deviation	2,6387.33		5,182.099		
Total deaths	24,621	81.08 (1)	3,533	18.92 (1)	28,154
Mean of deaths	5,013.71		504.714		
Standard Deviation	2,783.77		340.12		
Total population	31,265,000		19,229,711		

Note: The arithmetic mean of days over PM10 or ozone thresholds for cities determines which regions are considered high or low in terms of air pollution; (1) this percentage is computed taking into account the number of deaths and the number of infected people weighted with the population of these group of regions.

Total Deaths: Similarly, the death toll in high-pollution regions is notably higher, with 24,621 deaths, representing 81.08% of total deaths. Low-pollution regions account for just 18.92% of deaths, or 3,533 deaths. The average number of deaths in high-pollution areas is 5,013.71, with a high standard deviation of 2,783.77, indicating a wide range of outcomes across the regions. Low-pollution regions report an average of 504.714 deaths, with a much lower standard deviation (340.12), suggesting more uniformity in the death rates across these areas.

Population Data: The total population of high-pollution regions is 31,265,000, while low-pollution regions have a population of 19,229,711. The higher population in high-pollution regions contributes to the higher total number of infections and deaths observed in these areas.

In conclusion, the data suggest a clear disparity in the health outcomes related to COVID-19 between regions with high and low air pollution, with regions experiencing higher pollution levels accounting for a disproportionately large share of total infections and deaths. The higher number of infections and deaths in high-pollution areas may point to the compounded effects of environmental factors on public health during the pandemic, highlighting the need for more targeted health interventions in these regions.

Data presented in Table 8 depict a concerning trend: approximately 74.5% of COVID-19 infections and 81% of related fatalities in Italy concentrated in regions with high air pollution levels. This observation aligns with emerging research suggesting that airborne pollutants may act as carriers for microorganisms. Studies posit that high concentrations of PM2.5 and PM10, typically found in heavily polluted environments, can impede microbial growth (Coccia, 2020; Frontera et al., 2020). However, the precise mechanisms by which air pollution influences COVID-19 transmission remain an active area of investigation.

The detrimental impact of air pollution on public health and the environment is now widely acknowledged (Zhu et al., 2020). These findings underscore the urgency for governments to prioritize regions with elevated levels of air pollutants like PM2.5, PM10, NO2, and O3. Such regions are demonstrably more susceptible to the adverse public health consequences of epidemics like COVID-19 (Zhu et al., 2020; Uçkaç et. al., 2023a; 2023b; Kargı et. al., 2023c).

To mitigate the amplifying effect of air pollution on airborne viral diseases, nations must implement sustainable policies focused on air quality improvement (Coccia, 2018, 2019). These policies should prioritize the reduction of air pollutants and the promotion of renewable energy sources and cleaner production practices (Wang & Zhu, 2020). As Julian A. Feingold stated, “Clean air is not a luxury; it is a right” (Feingold, 2011). Policymakers must prioritize this right for all citizens.

In industrialized cities, environmental policies for sustainable development should specifically address urban and regional climatology. Optimizing urban ventilation can dilute pollutants and heat, facilitating air exchange and reducing regional air pollution. This approach, as outlined by Gu et al. (2020), can potentially lessen the threat of accelerated viral transmission during fall and winter seasons.

The implementation of sustainable policies to reduce air pollutants presents a valuable strategy for controlling and mitigating the impact of infections, generating substantial environmental, health, and economic benefits. A study by Cui et al. (2020) in China demonstrates that reductions in ambient air pollution can prevent premature deaths and associated morbidity cases, translating to significant economic advantages. Their findings suggest that reducing PM2.5 concentrations to 15 μg/m3 could result in substantial reductions in PM2.5-related mortality and morbidity, along with substantial economic benefits.

In conclusion, this study sheds light on geo-environmental factors that may exacerbate the spread of COVID-19 and similar viral agents. The research revealed a correlation between higher infection rates and several factors in Italian provincial capitals: elevated air pollution levels, hinterland location (particularly bordering large urban areas), low average wind speed, and lower temperatures. Notably, the northern Italian region studied, and regions with high air pollution in general, should strive to limit PM10 and ozone exceedances to less than fifty days annually to minimize the risk of accelerated viral transmission dynamics.

It is important to acknowledge the limitations of this study. Further research is necessary to definitively elucidate the complex relationships between infected individuals, environmental factors, demographics, and geographical characteristics that influence the spread of COVID-19. Effectively addressing the current COVID-19 pandemic and future similar outbreaks necessitates a multifaceted approach that integrates medical research and practice with disciplines such as immunology, biochemistry, molecular biology, and, crucially, the development of robust environmental policies for a sustainable society.

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