REVIEW

ENVIRONMENTAL PROGRESS
& SUSTAINABLE ENERGY

How changes in human activities during the lockdown impacted air quality parameters: A review

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Abstract

The health emergency linked to the spread of COVID-19 has led to important reduction in industrial and logistics activities, as well as to a drastic changes in citizens' behaviors and habits. The restrictions on working activities, journeys and relationships imposed by the lockdown have had important consequences, including for environmental quality. This review aims to provide a structured and critical evaluation of the recent scientific bibliography that analyzed and described the impact of lockdown on human activities and on air quality. The results indicate an important effect of the lockdown during the first few months of 2020 on air pollution levels, compared to previous periods. The concentrations of particulate matter, nitrogen dioxide, sulfur dioxide and carbon monoxide have decreased. Tropospheric ozone, on the other hand, has significantly increased. These results are important indicators that can become decision drivers for future policies and strategies in industrial and logistics activities (including the mobility sector) aimed at their environmental sustainability. The scenario imposed by COVID-19 has supported the understanding of the link between the reduction of polluting emissions and the state of air quality and will be able to support strategic choices for the future sustainable growth of the industrial and logistics sector.

KEYWORDS
air quality, atmospheric pollutants, COVID-19, COVID-19 conseguences, environmental impact, lockdown

1 | INTRODUCTION

A cluster of citizens affected by a new form of disease was first detected in Wuhan (China) in December 2019.[1] The World Health Organization (WHO) called it SARS-COV-2 and the disease COVID-19. Among the possible causes of COVID-19 (primarily a respiratory disease), air pollution has been analyzed as a possible means of spreading and cause of susceptibility to the disease.[2-4] In fact, there is a large amount of evidence of the relationship between air pollution and increased susceptibility to exposure to respiratory diseases and, now, to COVID-19.[5-13]

Since, during the acute phase of the spread of COVID-19, effective medicines and vaccines were not available to deal with the epidemic and reduce the negative impact on the infected, the solution recognized as the most effective to follow was that of social distancing (or lockdown), a practice that limits human interactions and contacts at close distances.[14-16]

These lockdowns, by imposing limitations on, or blocking, industrial and logistical activities and bringing in many social restrictions among citizens, had a strong impact on the economic and productive aspects of the countries.

The containment and contrast measures introduced to limit the spread of COVID-19 have caused a double negative shock on the global industrial and economic sectors, with consequences on the related supply chians[17]: on the demand side, with the postponement of consumer spending decisions, the closure of numerous commercial activities (in the catering, accommodation, transport, cultural and entertainment sectors) and the elimination of tourist flows. On the supply side, with the blocking of numerous production activities, both by decree and to allow the sanitation of the workplaces of operating companies. Initial disruptions in GSCs started on the supply side with factory closures in China,[18] instituted to slow the spread of COVID-19. As reported by The Economist Intelligence Unit[19] there are four major routes through which China has impacted the global economy: (1) the China's role as an international supplier of goods; (2) China's role as a major consumer of imported goods and commodities; (3) China's role as the world's biggest source of tourists; (4) worsening of investor and business confidence, increasing volatility on international financial markets. The effects have spread and amplified internationally, causing some enterprises to slow production or cease operations altogether.[20]

The critical issues on the supply side arose through the lack of parts and equipment to downstream industries (e.g., automotive, chemicals, IT, textiles, machinery, metal and metal products industries). The critical issues on the demand side concerned a wide range of primary extractive, manufacturing and service industries (e.g., demand for materials such as copper and nickel, oil and dairy products).[18] Estimates released by the ILO (International Labor Organization) quantify for the European Union a 50% drop in sales in the textile and clothing sector for 2020.[21] In the case of services, tourism and aviation suffered a strong negative shock. The estimates provided by the United Nations World Tourism Organization (UNWTO) impute a loss of 850 million–1.1 billion of international tourist arrivals, $910 million–$1.1 trillion in export revenues, and 100–120 million jobs.[22]

Global manufacturing output growth, according to data released by the United Nations Industrial Development Organization (UNCTAD) for the first quarter of 2020, had a sharp drop of 6% due to economic lockdown, with estimates reaching global reductions of 5%–15%. This is the second-most significant drop in recent history (after the 7% of the 2008/2009 financial crisis). In the first quarter of 2020, industrialized economies recorded a 2.5% contraction in manufacturing production (−2.4% in North America, −4.4% in Europe, −14.1% in China).[23] The data released by ILO (International Labor Organization)[18] quantifies for 2020 a global job loss of 8.8% which corresponds to 255 million full-time jobs (four times higher than those recorded during the world financial crisis of 2009). In particular, these consequences have been particularly concentrated in Latin America and the Caribbean, in southern Europe and in southern Asia.

This trend in industrial and economic sectors is confirmed by a relevant reduction in the electrical energy demand and supply: in 16 European Countries, a drop in nuclear and coal power production and distribution has been correlated with the stop of the non-essential production activities by Werth et al.[24] Kanitkar[25] estimates that, in India, during the first pandemic lockdown the daily supply from coal sourced power plants has reduced by almost 26%. This situation recovered during the central months of the year, but the current second peak of infections is again negatively affecting trends.

From the logistic point of view, several studies have been done to understand the impact of the lockdown on the movement of people and goods. A study by the International Energy Agency[26] reports that global road transport activity at the end of March 2020 during the COVID-19 emergency fell by 50% compared to the same period in 2019. Marinello et al.[12] analyzed the specific case of the city of Reggio Emilia (Italy), reporting a general decline in light and heavy vehicles moving inside and outside the urban area. Public transport was also very affected, with very high percentages of less use of means: in the study presented by Aloi et al.,[27] it is reported that Wuhan (China) and Delhi (India) registered reductions of 80–90% in the number of users. Flight activity decreased by about 75% compared to the previous year and a expected passenger revenue loss for 2020 have been estimated in $113 billion.[28] Also the freight transport has suffered serious consequences, in particular through a reduction in sea shipments[29] (eg in the first months of 2020, the total container volumes handled at Chinese ports dropped by 10%[30] while the total volume of goods decreased by 19.7%[17]) and the air cargo volumes (in the EU they decreased by 53% and by 3% in the United States[29]).

Production and transport activities have a direct relationship with the air quality. By analyzing the atmospheric pollutants emission inventories, it is possible to identify the impact of each activity on the emissions of substances harmful to air quality. Figure 1 reports the impact of these activities at European level.[31] The main industrial and logistical impacts are the following:

- Industrial processes and product use: NMVOC (44%) and $PM_{2.5}$ (12%)
- Energy use in industry: SO_x (20%) and NO_x (12%)
- Road transport: NO_x (36%) and $PM_{2.5}$ (11%)
- Non road transport: NO_x (9%)

Overall, this condition has generated a strong impact on environmental quality, with positive effects on numerous environmental matrices such as soil and water,[32,33] but also negative, for example on waste management.[34,35] Since there is a direct relationship between human activities and emissions of air pollutants, this blocking condition has favored a significant improvement in environmental quality.[36-44,45-47]

In order to understand the (positive or negative) effect of environmental and socio-economic factors on air quality, approaches are needed that make it possible to connect these aspects, providing an overall assessment in particular of the effect of policies and strategies
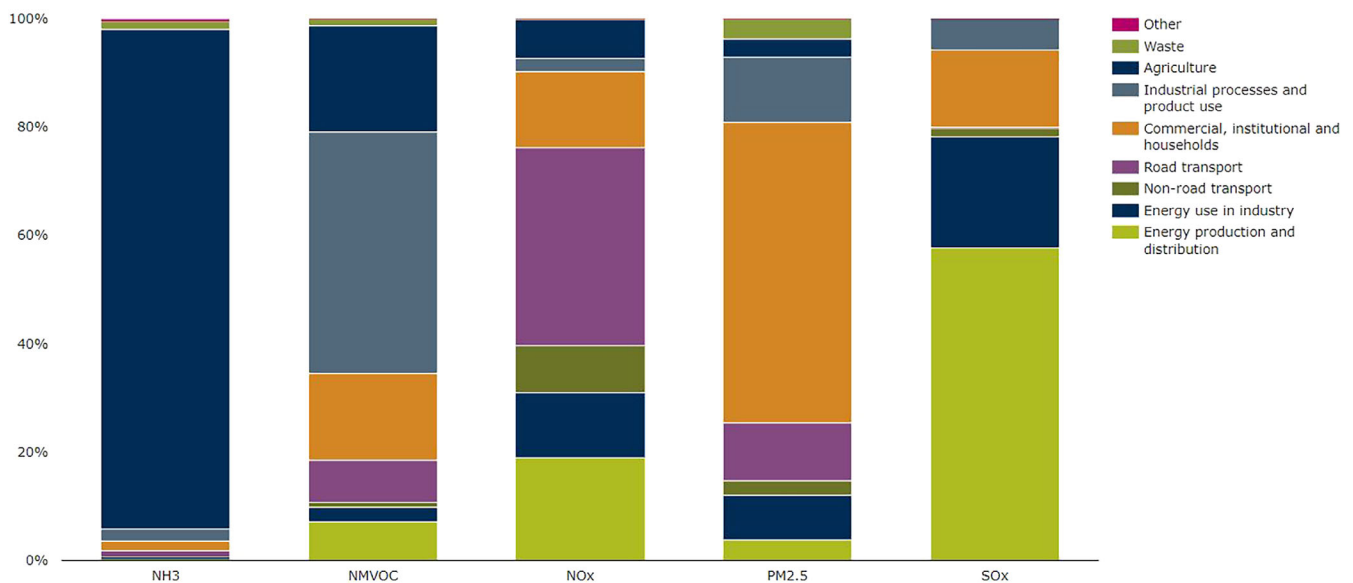
FIGURE 1 Emissions of the main air pollutants by sector group in the EEA-33[31] [Color figure can be viewed at wileyonlinelibrary.com]

for improving the air quality. As described by Wang et al.,[48] some commonly used approaches include regression analysis, spatial econometric models, Environmental Kuznets Curve (EKC),[49] and many others. To overcome some limitations that characterize these approaches, Wang et al.[48] proposes and experiments with the use of the Geographical Detector as a new and alternative tool. As reported by Zhan et al.,[50] the positive relationship between air pollution levels and a different socioeconomic factors has been discussed by several authors, as well as the negative association between air quality and natural factors. This knowledge also allows to make forecasts on pollution levels starting from the study of the evolution of socioeconomic and natural factors used as proxy variables.[51]

Starting from the above-described aspects, the aim of this article is to review the scientific literature analyzing the effect of the lockdown on industrial and logistical activities (including the issue of citizen mobility) and, consequently, on the state of air quality as a direct consequence.

The contribution of this article on the scientific literature is a critical and global reading of the studies that have been conducted on the evaluation of the effect of the lockdown on air quality. Through this review, scholars have at their disposal a complete representation of the trends in the concentrations of the main air pollutants in various international regions, favoring a dissemination of knowledge on this recent problem. The identification of the main industrial and logistical causes also helps to define a link between emission sources and the effect on air quality.

The use of the results of this research can support researchers in understanding the effect that the reduction of some of the main sources of impact on air pollution can generate on the concentrations of atmospheric pollutants and how these effects have a common behavior, but with specific influences due to specific territorial

characteristics (in particular the meteorological parameters and the presence of other pollutants that may be precursors in the formation of secondary pollutants as in the case of ozone).

2 | METHODOLOGY

2.1 | Scope of review

In response to the recent emergency scenario that has developed internationally, the reference scientific bibliography has undergone a rapid increase in the available contributions, favoring highly specific knowledge and many case studies distributed globally. The purpose of the review is, therefore, to allow a detailed collection of available contributions, selecting and analyzing them through the use of a structured and detailed methodological approach.

2.2 | Material search and selection

Table 1 shows the approach adopted to identify and select the articles used in this review work. The research of the papers was completed on November 10, 2020 using the ScienceDirect and Scopus databases and without applying any limitations on the type of journal, year and type of publication.

The identification of the papers has been carried out using 15 keywords, obtained by combining two groups of words, called "group A" and "group B". The first group focuses research on COVID-19, while the second group specializes in research on the specific topic of air quality and concentrations of polluting substances in the atmosphere.

TABLE 1 Research and selection protocol

A Database				
A1.	ScienceDirect			
A2.	Scopus			
B Search criteria				
B1.	Journal		All	
B2.	Year		All	
B3.	Article type		All	
B4.	Date of search		10th November 2020	
C Keywords for papers identification				
	Group A		Group B	
	COVID-19		Air pollution	
	Lockdown		Air quality	
	SARS-CoV-2	AND	Environmental impact	
			NO_2	
			$PM10$	
D Steps for material selection				
D1.	Duplicate removal			
D2.	Keywords and highlights assessment			
D3.	Application of inclusion criteria on the content of the text			
		D3.1	Treats the air quality of specific areas	OR
		D3.2	Assess the effect of COVID-19	OR
		D3.3	It evaluate the results quantitatively	
D4.	Full text assessment			
E Other paper sources				
E1.	From informal approach			
E2.	From browsing method			
F Descriptive analysis				
Year				
Journal				
Country type				
	Research paper			
	Review			
	Others			
G Case studies analysis				
Location of the case studies	Location of the case studies			
Impact of lockdown on logistics and industrial/economic activities	Impact of lockdown on logistics and industrial/economic activities			

All the papers identified as potential for review have been analyzed by applying a scalar approach consisting of numerous steps (point D of Table 1), analyzing more and more in detail the articles collected and eliminating those inappropriate. The first step eliminates duplicate papers, selected on both databases used or by the use of different keywords in the search. It is a process that eliminates many results. The remaining papers have been evaluated through the keywords and highlights to understand the content and results discussed by the authors and to verify if the results obtained could be useful for this study. Therefore, on the content of the text, some inclusion criteria have been applied to evaluate in depth the

detail of the data processed by the authors. In particular, the papers that analyzed the air quality in different areas, evaluating the effect of COVID-19 and providing quantitative results, have been considered suitable. Papers that did not provide these indications have been discarded. The entire text has been analyzed only on the residual papers.

Finally, a further enrichment of the contributions has been conducted through browsing other known references and tracking down references in the selected papers. A total of 101 papers resulted from keywords search and selection, while other 20 from informal and browsing methods, for a total of 121 papers analyzed.

2.3 | Material analysis

The review analysis was conducted on the collected material by applying the evaluation approach shown in Table 1.

The descriptive analysis provides a summary representation of the main elements characterizing the selected articles, in particular for the characteristics of the publication, the country of origin of the corresponding author, the type of publication and its origin (expressed as a form of collection).

3 | RESULTS AND DISCUSSION

This section describes the results of the papers analyzed with respect to each element reported in Table 1 with the aim of answering the identified research questions.

3.1 | Descriptive analysis

Considering the recent evolution of the health emergency connected to COVID-19, the papers analyzed have been published during the year 2020 (83% of the selected papers), while the remaining part of 17% is scheduled to be published in 2021.

The distribution of the papers compared to the publication journals shows that "Science of the Total Environment" is the journal with the highest frequency of articles (about 41%), followed by "Environmental Pollution" (5%), "Atmosphere" (4%) and "Environmental Research" (4%). Other journals are present with less publications each.

The distribution of the papers with respect to the author's country of origin highlight a marked prevalence of authors from countries initially seriously affected by the health emergency (China, India, USA, Italy, Spain). China and India, together, concentrate 50% of the research analyzed. From the point of view of the type of paper, 111 papers are classified as "research paper", 7 as "short communication" and 3 as "review". In particular, some authors,[15,52-56] presented short communications describing the effect of lockdown on air quality. The review papers are the works presented by Arora et al.,[46] which analyze the effect of the health emergency on the global environment (air pollutants, ozone layer, water, industrial, noise pollution and wildlife), by Paital[57] that analyses several aquatic and terrestrial environmental parameters such as pH, surface type, temperature and air pollution, and by Rume and Islam[58] who analyze the effects of the lockdown on environment.

3.2 | Case study analysis

This evaluation aims to provide a descriptive representation of the main results reported by the scientific literature on numerous case studies distributed internationally.

Analyzing the case studies available in the literature, Table 2 and Figure 2 report the study area and their spatial resolution. China is the most analyzed territory (28% of selected papers), followed by India (21%), Italy and the United States (12% each) and Spain (8%). These five countries represent over 80% of the total papers collected in this review and coincide with the countries that were initially the most affected by the spread of the epidemic. From the point of view of the spatial domain, urban areas, especially large megacities, are the most analyzed case studies (about 55% of selected papers). Delhi is the most investigated city (about 12% of papers studied this area), followed by Wuhan (11%), Mumbai (10%). Milan, London, Barcelona and Madrid are the European cities with the largest studies (about 3% each). In the Americas, the two main cities of Brazil (Rio de Janeiro and Sao Paulo) and New York have been studied most frequently. A discussion of some of these cities is reported in the following section. Figure 3 and Table S1 report the main effects induced by the lockdown on human activities. All the papers identify the lockdown as the cause of a significant reduction in the industrial and economic activities of each study area, as well as the decrease in road transport which led to a lowering of atmospheric pollutant emissions which favored a substantial improvement in the air quality status (as reported in Table 3 and Figure 4). In particular, Baldasano[13] studying the areas of Madrid and Barcelona, indicates a significant impact from the closure of manufacturing, commerce and construction industries, as well as from old traffic. Still analyzing the Spanish territorial context, Briz-Redón et al.,[59] attribute the reduction of NO_2 concentrations to the suspension of many combustion processes, such as vehicles, industrial boilers, power plants and ships. Chen et al.,[60] analyzing the profiles of NO_x concentrations in Shanghai, attributes them to the nearby industrial parks, ports and to the heavy duty truck transportation. Through a statistical approach, Wang et al.[61] demonstrate in China a significantly positive relationships of industrial activities with Air Quality Index (AQI), CO, NO_2, SO_2 and $PM_{2.5}$ concentrations. In India, Mor et al.[62] attribute the maximum decrease of air pollutant to the restriction on automobiles and the shutting of industries.

Table 3 shows the pollutants used to characterize the air quality. They are extremely numerous: over 17 air pollutants are described in the selected literature. Among these, however, there are some compounds that have been used more frequently. Specifically, nitrogen dioxide (NO_2) is the most widely analyzed, with over 85% of the investigated authors reporting data for this pollutant (in some cases, in addition to NO_2, the concentrations of nitrogen monoxide (NO) and consequently of nitrogen oxides (NO_x) have been analyzed). The choice of this pollutant is linked to the widespread availability of air quality monitoring points at a global level that measure this pollutant and that make data available in almost real time, in addition to being a good indicator of the pollution caused by various anthropogenic sources (in particular for industrial and household combustion processes and for vehicular traffic). The particulate matter $PM_{2.5}$ represents the fine fraction of the atmospheric particulate and, as in the case of NO_2, widespread use of it has been found in the studied bibliography: about 69% of the authors investigated data provided for this pollutant. Particulate PM_{10}, ground-level ozone (O_3), sulfur dioxide (SO_2) and carbon monoxide (CO) complete the group of the most analyzed pollutants (51%, 41%, 36% and 40%, respectively). Black carbon (BC), ammonia (NH_3), volatile organic compounds (VOCs),

TABLE 2 Characterization of case studies

AMERICAS		
Continent or country	USA	33,53,57,86-90
	Canada	57
	Colombia	72
	Argentina	91
Region	California	54,92
	Some US states	93
	Ontario region	73
City	New York	65,81,94
	Los Angeles	81,94
	Somerville	95
	Mexico city	81,96
	Rio de Janeiro	97,98
	Sao Paulo	81,85
	Bogotá	99
	Medellín	99
	Quito	100,101
	Lima	81,102
	12 Ecuadorian cities	103
ASIA AND OCEANIA		
Continent or country	Asia	104
	India	46,105-107
	China	33,53,61,67,89,108-112
	Japan	57,64
	Korea	57,113
	Bangladesh	114
	Australia	57
Region	YRD region	115
	Beijing-Tianjin-Hebei region	116,117
	Regions of India	76
	Hat Yai region	118
City	Shanghai	15,80,81
	Beijing	81,94,119
	Wuhan	53,75,79,81,84,119-123
	Guangzhou	119,124
	Shijiazhuang	125
	Hangzhou	126
	Some Chinese cities	43,127-130
	Seoul	75,131,132
	Daegu	131
	Tokyo	75
	Hong Kong	52,5752
	New Delhi	56,69,81,82,94,120,133-135
	Mumbai	82,94,134-136
	Chennai	135,137
	Ghaziabad	45
	Chandigarh	62

TABLE 2 (Continued)

AMERICAS		
	Ahmedabad	74
	Gujarat	138
	Kolkata	135
	Some Indian cities	136,139-142
	Dubai	94
	Tehran	81
	Baghdad	66
	Kathmandu	143
	Almaty	78
	Chittagong	144
	Dhaka city	145
EUROPE		
Continent or country	Europe	47,53,57,110,146
	Spain	33,53,147,148
	Italy	33,53,148
	France	53,148
	Germany	148
	UK	55,149
Region	Lombardy region	150,151
	Veneto region	151
	Emilia-Romagna region	151
City	London	81,120,136
	Paris	81
	Barcelona	13,83
	Madrid	13,81
	Zaragoza	94
	Valencia	84
	11 Spanish cities	59
	Berlin	81
	Düsseldorf	152
	Moscow	81
	Graz	153
	Milan	63,77,154
	Rome	81,84,94
	Turin	84
	Florence	19
	Padova	155
	Pisa	19
	Lucca	19
	Brescia	156
	Palermo	157
	5 Polish cities	68
	Istanbul	70,81
	Athens	158
	Nice	84

(Continues)

TABLE 2 (Continued)

AMERICAS		
AFRICA		
Continent or country	Egypt	159
City	Salé City	160
	Johannesburg	81
INTERNATIONAL		
	Various international cities	161-165

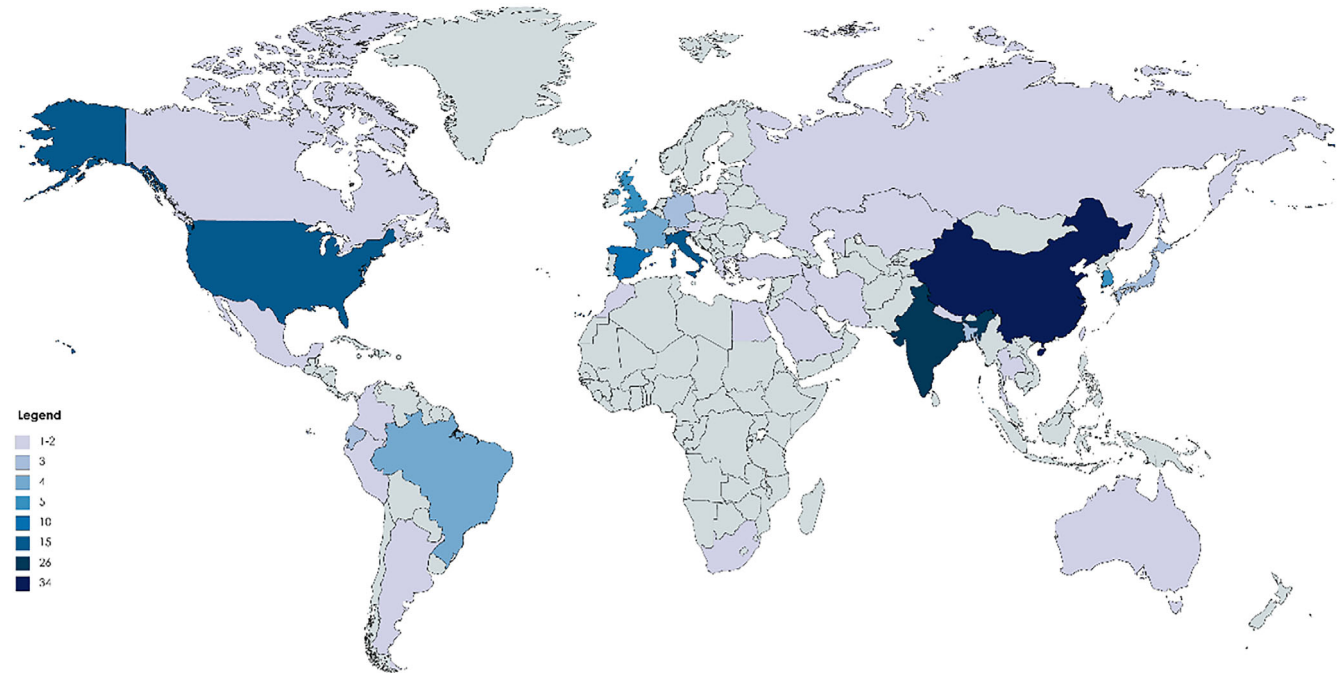**FIGURE 2** Spatial coverage of the case studies available in literature [Color figure can be viewed at wileyonlinelibrary.com]
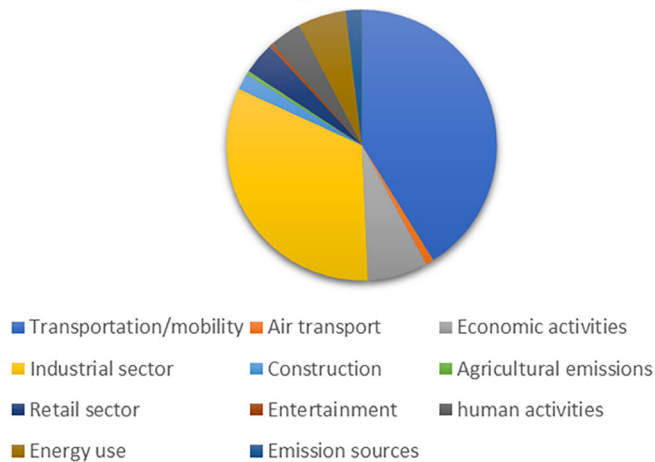

FIGURE 3 Consequences of the lockdown on logistic and industrial activities [Color figure can be viewed at wileyonlinelibrary.com]

benzene-toluene-ethylbenzene-xylenes (BTEXs), carbon dioxide (CO_2) and lead (Pb) are the other pollutants described, but with very low percentages. At most, 4% of the authors studied these compounds.

Reference 62 analyze 14 air pollutants, including particulate matter (PM_{10}, $PM_{2.5}$), trace gases (NO_2, NO, NO_x, SO_2, O_3, NH_3, CO) and VOC's (benzene, toluene, o-xylene, m, p-xylene, ethylbenzene), to study the variation in ambient air quality during COVID-19 lockdownwas in Chandigarh (India). Collivignarelli et al.[63] who analyze the effect of air quality lockdown in the Metropolitan City of Milan (Italy), provides an overall assessment for nine pollutants. Table 3 shows the trend in the concentrations of each pollutant during the lockdown period with different colors, compared to periods prior to the epidemic. This allowed to highlight (often also quantitatively) a characteristic behavior for some of the most studied pollutants.

It is interesting to observe how the authors agree on the general reduction of the concentrations of NO_2, PM_{10}, $PM_{2.5}$, SO_2 and CO. All the studies that analyze NO_2 agree in identifying a general trend towards a reduction in concentrations. The only exceptions

TABLE 3 Results from case studies: pollutants analyzed by each study

Reference	Pollutant						
	PM_{10}	$PM_{2.5}$	NO_2	SO_2	CO	O_3	Others
73		X	X			X	
74	X	X	X				
86		X	−65%				
46	X	X	−36%	X	X	X	
72		−13% / -86%					
64		X	X				NO, NO_x
80	X	X	X	X	X	X	
13	−43%	−31%	−18%		−10%	Factor of 1.5−2	
127							
87		X	−25%				
105			−12%				
120	X	−8%	X	X		+14%	
91	X		X				
150	X						
121			X	X	X		
59	X		X	X	X	X	
156	X	X	X				
94		X					
60		X	X	X	X	X	
88			−49%		−37%		
89	−31%	−39%					
108		−29%	−50%	X	X		
63	X	X	X	X	X	X	NO_x, Benzene
161			−2% / -70%				
109		X					
97	X	X	X		X	X	
19	X	X	X			X	
159			−45%		−46%	−61%	
99	−44%	−40%	−60%				
151			X				
68	−9% / -21%	−11% / -26%	−10% / -19%	X			
81	X	X	−12% / -60%	X	X		
143	X	X					
75			−19% / -83%	−71%	−4%		HCHO
110		X					
69	−60%	−60%	−40%			−40%	
111		−30%	−17%				
158			−35%		−35%		
132		−10%	−17%		−16%		
66	−15%	−8%	−6%			+13%	
129		X					
67			−90%				
52	X	X	X	X	X	X	
95							Ultrafine particle
114			−40%	−43%		+7%	

(Continues)

TABLE 3 (Continued)

Reference	PM$_{10}$	PM$_{2.5}$	NO$_2$	SO$_2$	CO	O$_3$	Others
113	−35%	−45%	−20%	X	−17%	X	
104	−31%	−32%	−64%	−20%	−31%		
70	X		−12%				
78		−21%	−35%	X	−49%	+15%	BTEX
141	X	X	−45%				
142		−10% / -54%					
82	−55%	−49%	−60%	−19%			
162			X		X		Aerosol
137	X	X					
115		−32%	−45%	−20%			
122			X				
125		−30%	−60%	−20%	−42%		NO, NO$_x$, CO$_2$, OC, EC
163	−14% / -20%	−7% / -16%	−23% / -37%	−2% / -20%	−7% / -11%	+10% / +27%	
92		−19%	−16%		−25%		
45	X	X	X	X			
153	−14%		−41%			+34%	
133	−50%	−50%	X		X		NH$_3$
139	X	X	−57%	X	−30%		NO, NH$_3$
147	X	X	X	X	X	X	
144	−32%	−40%	−13%	X	X		
47	X	X	X			X	
62	−36%	−28%	X	X	X	X	NO, NO$_x$, NH$_3$, VOCs
53			−30%				
152			−50%				
85	X		−54%		−65%	+30%	NO
106	X	X	−20%	X	X	X	
128	X	X	X		X	X	
148			−55%			X	
160	−50%		−50%	−50%			
103			−13%				
57	X	X	X				
54		X				X	
119		X	X	X			
96			X		X	X	
56		−50%					
145		−26%	−20%	−17%	−9%	−10%	
164		−12%					
55	X	X	−50%			+20%	NO, NO$_x$
155	−10%		−50%				NO, NO$_x$
100		X	X			X	
165	X	X	X		X		
134			−50%				
136	X		X				
107	−40%	−44%	−51%	−21%			
138	X	X	−30% / -84%	X	X	+16% / +58%	

TABLE 3 (Continued)

Reference	PM$_{10}$	PM$_{2.5}$	NO$_2$	SO$_2$	CO	O$_3$	Others
131	X	−36%	X		X		
140	X	X	X	X	X		
134			−50%				
84	−8% / -42%	−8% / -42%	−56%			+17 / +36%	NO
98			X			X	NMVOC
76	X	X	X	X	X	X	
135	X	X	X	X	X	X	
93		−12%				X	
118	−23%	−21%	−33%				
79	−33%	−41%	−50%		−16%	+149%	
83	X		−50%	X		+50%	BC
102	X	X	X	X	X	X	
146			−85%				
157	−45%		−50%		−51%		
61	X	X	X	X	X	X	
112			X				
43		X				X	
116	−33%	−21%	−38%		−20%		
149			−14% / -38%				
90		−33%	−29%		−17%		NO, NO$_x$
136	−50%	−50%	−65%				
126	−58%	−47%	−83%	−11%	−30%	+125%	
101		−29%	−68%	−48%	−38%		
33		X	X				
65		X	X				
124	−30%	−37%	−52%	−29%	−33%	X	
130			X			X	
117		X	X	X	X	X	
123		X					
154	X	X					
77			X			X	

Note: Concentration values worsened during lockdown were indicated in red, unchanged values in yellow and decreasing values in green and, when available, the relative percentage values.

(indicating similar values) are the works of Azuma et al.[64] and Zangari et al.[65] For NO$_2$, the minimum reduction (−6%) has been reported in the study by Hashim et al.[66] that studies the impact of COVID-19 lockdown in Baghdad (Iraq). The maximum value has been reported by Huang et al.[67] which, studying the area of East China, found a 90% reduction in NO$_2$ concentrations. PM$_{10}$ range from negative percentage differences of 9%[68] to 60%.[69] Only the study by Kuksan and Ulutaş[70] does not detect significant changes. For PM$_{2.5}$, the differences range between −7%[71] and − 86%.[72] Adams[73] and Aman et al.[74] found no differences. SO$_2$ and CO also have a general tendency to decrease. The minimal difference (−2%) is described in the study by Chitra et al.,[71] while the maximum (−71%) is described by

Ghahremanloo et al.[75] Singh et al.[76] found no differences. O$_3$ is the pollutant that most frequently reports increasing percentage values during the health emergency period. On average, a 47% percentage increase is reported. Manut et al.[47] reports data for various European countries, with percentage variations ranging from −2.7% in Ireland to +17.6% in Belgium. Zoran et al.,[77] describing the situation at Milan city (Italy), reports an increase in concentrations by a factor 2.25.

From the percentage differences reported by the authors, some situations are evident in which the variations in the concentrations of different pollutants are very significant (close to or greater than 100%). Particularly significant negative percentage differences, indicating a reduction in pollutant concentrations as a result of the

Variation in pollutant concentrations
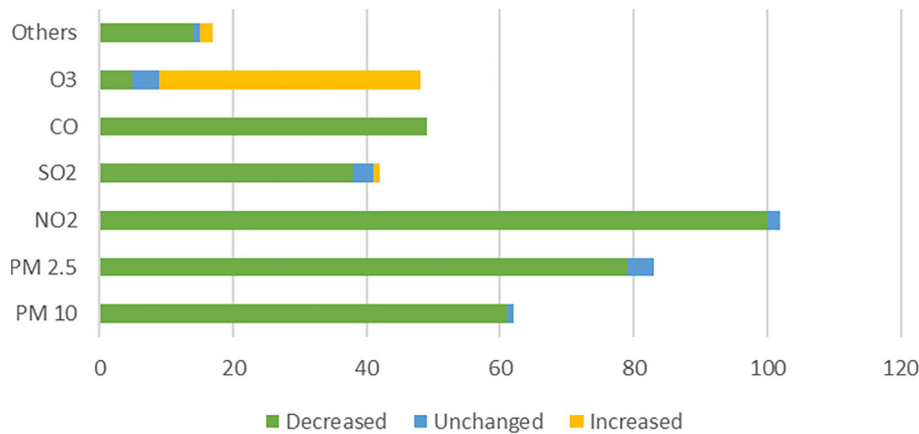
FIGURE 4 Variation in pollutant concentrations [Color figure can be viewed at wileyonlinelibrary.com]

lockdown, are mainly linked to NO_2 and $PM_{2.5}$. There are several authors who highlight differences between −83% and − 90%. The causes of these differences are attributable to the following reasons:

- The considerable reduction of some pollutants is attributed by the authors analyzed to particular local conditions that determine (under normal conditions) high concentrations of NO_x and $PM_{2.5}$ (especially in large Asian urban areas) which, with the blocking of many activities, have suffered strong reductions in polluting emissions. This decline is also due to the combined contribution of the lockdown and the benefits induced by the clean air regulations. Finally, meteorological variables are considered important elements in determining this trend.
- The significant increase in O_3 concentrations is due to the sharp reduction in NO and $PM_{2.5}$ concentrations, while VOCs remain available.

Finally, Table S2 shows the reference time periods used by each study to evaluate the air quality of its case studies. In particular, the months of the year 2020 during which the representative data of the -COVID-19 condition have been collected, as well as the relative comparison periods with respect to previous years. The period of greatest interest begins with the third week of March and ends after the first week of April. Seventy-six percent of the authors analyze the polluting concentrations covering this period (in some cases not every day of the period).

3.3 | The most analyzed cities

As reported in the previous section, cities have been extensively studied by numerous authors.

Some representative aspects of cities present in some areas heavily impacted by the COVID-19 emergency are described below and, therefore, particularly analyzed in the literature.

Wuhan has also been the subject of many studies. Again, the literature agrees on the observed results, although the percentages vary

between studies. $PM_{2.5}$ decreased between −8%/−42%, PM_{10} between −33%/−42%, NO_2 decreased between −50%/−83%, SO_2 decreased by 71% and CO decreased between −4%/−16%. The authors identify an increase in ozone concentrations, with very different percentage values: +14% in the study by Kerimray et al.,[78] up to the maximum increase of +149% reported by Sulaymon et al.[79] Shanghai is another city described in the literature by various studies.[15,80,81] Bai et al.[80] conducted a study in different regions (downtown, suburbs) of Shanghai city in order to assess the airborne pollutant concentrations before, during and after the lockdown. The results showed a significant improvement in air quality, in particular for $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO. Ozone is the only pollutant that has increased its concentrations. In general, some differences in concentration changes were found in the downtown region and the suburbs of Shanghai. Chauhan and Singh[15] analyzed several cities around the world, including Shanghai, which found a marked reduction in air pollution attributed to the reduction of emissions in transport and industries. Fu et al.[81] analyzed several international cities, highlighting the significant drop in pollutant concentrations.

Delhi is the city that has focused the attention of many studies. All, although the time periods studied are slightly different, agree on the observed results. In particular, a reduction between −25%/−60% was observed for $PM_{2.5}$, between −36%/−60% for PM_{10} and between −40%/−65% for NO_2. SO_2 is decreasing, but only Kumari et al.[82] provides a quantitative value (−19%). For the ozone, there are conflicting indications: Kerimray et al.[78] reports an increase in O_3 values during lockdown, while Goel[69] indicates that the ozone levels were reduced by 30–40%. For Mumbai PM_{10}, $PM_{2.5}$ and NO_2 values have been reported ranging from −36%/−50%, −10%/−50% and − 40%/−65%, respectively. Mumbai has also concentrated several assessments on its territory, where the trends in the reduction of pollutant concentrations are confirmed, except for O_3 which has a growing trend. The NO_2 trend decreased on average by 60%, particulate matter decreased by about 50% and SO_2 by about 19%.

The Spanish territory was investigated through studies conducted in the cities of Barcelona, Madrid, Zaragoza and Valencia. Baldasano[13] investigated the trend of NO_2 in Barcelona and Madrid, highlighting

how the drastic reduction in road traffic favored the reductions of NO_2 concentrations of 62% and 50%, respectively. Tobias et al. and Fu et al.[81,83] contributed to the study of these two Spanish cities. New data on Barcelona have been integrated, highlighting a reduction of about 30% of PM_{10}. Ozone levels increased of 33%–57%. The Italian territory has also been extensively analyzed, through case studies in numerous cities. In particular, Milan and Rome are the cities most investigated with the evaluation of the trends of numerous atmospheric pollutants. Particulate matter, NO_2 and SO_2 have shown decreasing concentrations, while SO_2 has been reduced or constant compared to the periods before the lockdown, while O_3 is always increasing. Sicard et al.[84] reported quantitative data for the city of Rome and Turin, with the largest reductions in NO_2 (over 50%).

Even the Americas, due to the high number of infections and critical issues related to the COVID-19 emergency, has been the subject of many studies available in the literature. In the USA, Fu et al. and Zangari et al.[65,81] provided specific indications for the city of New York, highlighting the reduction in pollutant concentrations during the lockdown and, in particular, quantifying the NO_2 values in about −60%. Similar conditions were also relevant in the urban area of Los Angeles.

In South America, the cities of Rio de Janeiro and Sao Paulo in Brazil all pollutants showed decreasing trends, except for ozone which has increasing concentration values during the lockdown. In particular, Nakada and Urban[85] quantified the reduction of NO_2 at −54%, CO by −65%, while O_3 increased by 30%.

4 | CONCLUSIONS

This paper has been developed with the aim of collecting and describing in a synthetic and organized way the main evidences emerged in the literature about the effects of lockdown on industrial and logistical activities and the consequences on air quality. These aspects have been analyzed through the characterization of the case studies reported in the scientific literature, their geographical distribution, the main evidence on the state of air quality and on the impact on the spread of COVID-19. The results made it possible to highlight the strong scientific commitment to analyzing these aspects, with a significant presence of articles prepared by authors coming mainly from some of the areas most impacted by the health emergency (China, India, Italy, the USA). The geography of the case studies investigated also reflects the spatial distribution of the epidemic, focusing in particular on the urban areas of the megacities heavily populated and impacted by COVID-19 (e.g., Delhi, Wuhan, Mumbai with millions of inhabitants each). The blockage of production activities, the limitation of logistical activities and the closure of traffic are the factors that have strongly influenced the rapid improvement in air quality, thanks to the significant reduction of polluting substances.

This research also highlighted the widespread and common practice among authors of using specific air pollutants, in particular NO_2 and PM (both PM_{10} and $PM_{2.5}$), with a lower presence of SO_2, CO and O_3. Undoubtedly, the positive effect of lockdown on

environmental quality is confirmed, when analyzing its effects in the short term (especially March and April, which was the most widely investigated time frame). Most pollutant concentrations decreased during this period, in some cases very significantly (NO_2 and PM). O_3, on the other hand, showed the opposite behavior, with significant increases in the measured values. In fact, being a secondary pollutant heavily dependent on solar radiation (intensity and duration), this trend can be explained by the significant lower presence in concentrations of primary ozone precursor pollutants (e.g. NO) and by meteorological conditions. Finally, we want to underline how this condition (imposed by the health emergency) offered a very important opportunity to evaluate and "test" in a real context the possible effects of sustainable policies and strategies. The observed results allow to observe some effects on air quality and can become important decision-making elements for the planning and management of the territory and its activities. At the same time, important information can be provided to companies to identify the best technologies to improve their environmental performance.

AUTHOR CONTRIBUTIONS

Samuele Marinello: Conceptualization; data curation; methodology; writing-original draft. **Maria Angela Butturi:** Data curation; validation; writing-review & editing. **Rita Gamberini:** Conceptualization; investigation; supervision; validation; writing-review & editing.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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