How does atmospheric circulation affect the diffusion of Covid-19 in polluted cities?

By Mario COCCIA †

Abstract. This paper endeavors to explain how wind speed can affect the diffusion of COVID-19. The statistical analysis, based on data from Italy, suggests that high wind speed can reduce air pollution commingled with viral agents and as a consequence reduce infected individuals of COVID-19; moreover, results reveal that polluted cities with low wind speed have a greater number of infected individuals and total deaths also because of bad air quality. This study suggests the important role of atmospheric pollution and atmospheric circulation in the transmission dynamics of the novel Coronavirus to support appropriate environmental policy to reduce concentration of pollutants in the atmosphere, improving air quality and human health.

Keywords. COVID-19, Air pollution, Environmental pollution, Wind speed, Coronavirus, SARS-CoV-2, Public health, Air quality, Environmental science.

JEL. D81, D91, E71, G01, G41, H11, I18, Z18.

1. Introduction

The contemporary environmental and sustainability debate is based on new or relatively unexplored topics continually emerging. This study provides an investigation for the exploration of causes, consequences and policy responses linked to diffusion of Coronavirus disease 2019 in a context of environmental and sustainability science.

The Coronavirus disease 2019 (COVID-19) is due to a new virus called Severe Acute Respiratory Syndrome CoronaVirus-2 (SARS-CoV-2) that produces minor symptoms in most people, but is also the cause of death of many individuals (Ogen, 2020; Dantas et al., 2020). This Coronavirus Disease, started in China in 2019, is an on-going global problem for human health that is generating a socioeconomic crisis and negative world economic outlook projections (Saadat et al., 2020). Manifold studies suggest a possible relation between air pollution and diffusion of COVID-19 infection with severe respiratory disorders (Fattorini & Regoli, 2020; Frontera et al., 2020; Wang & Su, 2020). Scholars also state that high levels of air pollution can increase the lethality of COVID-19 infection (Contini & Costabile, 2020). Conticini et al. (2020) argue that population living in regions with high levels of pollutant has also a high probability to develop respiratory disorders because of infective agents. In fact, the highest level of COVID-19 infection is in the USA, Spain, Italy, UK, Russia, China, France,

† CNR, National research Council of Italy & Yale University School of Medicine, 310 Cedar Street, Lauder Hall, Suite 118, New Haven, CT 06520, USA.
☎: + 85287-4804  🆘: mario.coccia@cnr.it
etc. having in some regions a very high level of particulate compounds in the atmosphere (Frontera et al., 2020). Studies confirm correlations between exposure to air pollution, diffusion and virulence of SARS-CoV-2 within regions with population having a high incidence of respiratory disorders, such as chronic obstructive pulmonary disease (COPD) and Lung Cancer (Fattorini & Regoli, 2020). Ogen (2020, p.4) finds that high NO₂ concentrations in the atmosphere, associated with downwards airflows, cause of NO₂ buildup close to the surface and prevent the dispersion of air pollution, increasing mortality of COVID-19, such as in Italy, Belgium, etc. In particular, this geographical structure of regions associated with specific atmospheric conditions prevents the dispersion of particulate compounds, which are one of the factors of a high incidence of respiratory disorders and inflammation in population of some European areas, such as Norther Italy. In short, the exposure of air pollution and poor air quality can be a driver of high rate of mortality of Coronavirus infection, such as in Italy (13.91%), Spain (11.8%), UK (14.73%), Belgium (16.38%), etc. (cf., Center for System Science and Engineering at Johns Hopkins, 2020). The study by van Doremalen et al. (2020) revels that in China viral particles of SARS-CoV-2 may be suspended in the air for various minutes and this result can explain the high total number of infected people and deaths of COVID-19 infection in the USA, Spain, Russia, France, Brazil, Turkey, Iran, etc. (cf., Center for System Science and Engineering at Johns Hopkins, 2020). In general, these studies suggest the hypothesis that the atmosphere having a high level of air pollutants, associated with certain climatological factors, may support a longer permanence of viral particles in the air, fostering a diffusion based on mechanisms of air pollution-to-human transmission in addition to human-to-human transmission (Frontera et al., 2020). In order to extend the investigation of these critical aspects in the development of COVID-19 outbreaks worldwide, in the atmospheric environment with high levels of particulate compounds and specific climatological conditions, the goal of this study is to analyze the relation between infected people, wind speed in the atmosphere and air pollution that can explain some critical relationships determining the diffusion of COVID-19 infection and negative impact in environment and human health. This study has the potential to support long-run environmental policy directed to mitigation strategies of emissions and depositions of gaseous and particulate compounds in the atmosphere for reducing and/or preventing the diffusion of future epidemics similar to COVID-19 infection.

2. Study design

2.1. Data sources and research setting

This study focuses fifty-five (N=55) cities that are provincial capitals in Italy, one of the countries with the highest number of deaths of COVID-19 infection: more than 30,900 units at 12May, 2020 (cf., Lab24, 2020). Epidemiological data are from Ministero della Salute (2020); data of air pollution are from Regional Agencies for Environmental Protection in Italy.
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(cf., Legambiente, 2019); climatological information are based on meteorological stations in Italian provinces (il Meteo, 2020); and finally, data of the density of population are from the Italian National Institute of Statistics (ISTAT, 2020).

2.2. Measurements

- **Air pollution and particulate compounds emissions.** Total days exceeding the limits set for PM$_{10}$ or for ozone in 2018 per Italian provincial capitals. Days of air pollution are a main factor that affects atmosphere, environment and human health. Moreover, 2018 as baseline year for air pollution data, it separates out the effects of COVID-19 infection.

- **Diffusion of COVID-19 infection.** Number of infected individuals on March-April, 2020

- **Atmospheric circulation.** Average wind speed km/h on February-March 2020

- **Interpersonal contact rates.** Population density of cities (individual /km$^2$) in 2019

2.3. Primary data analysis and statistics

Descriptive statistics is performed categorizing Italian provincial capitals in groups, considering:

- **Atmospheric circulation - wind speed**
  - Cities with high wind speed in the atmosphere (>9 km/h)
  - Cities with low wind speed in the atmosphere (≤9 km/h)

- **Air pollution and particulate compounds emissions in the atmosphere**
  - Cities with high air pollution and particulate compounds emissions in the atmosphere (with >100 days per year exceeding the limits set for PM$_{10}$ or for ozone)
  - Cities with low air pollution and particulate compounds emissions in the atmosphere (≤100 days per year exceeding the limits set for PM$_{10}$ or for ozone)

Correlation and regression analyses verifies relationships between variables understudy. Regression analysis considers that the number of infected people across Italian provincial capitals (dependent variable $y$) is a linear function of the explanatory variable of total days exceeding the limits set for PM$_{10}$ (explanatory variable $x$).

The specification of linear relationship is a log-log model:

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

$\alpha$ is a constant; $\beta$= coefficient of regression; $u$= error term

The estimation of equation [1] is performed using a categorization of cities according to wind speed in the atmosphere. An alternative model [1] applies as explanatory variable the density of population per km$^2$ considering groups of cities with high or low air pollution and particulate compounds emissions in the atmosphere.
Ordinary Least Squares (OLS) method is applied for estimating the unknown parameters of linear models [1]. Statistical analyses are performed with the Statistics Software SPSS® version 24.

3. Statistical analyses

Table 1 shows that cities in regions with low wind speed in the atmosphere have a higher level of days of air pollution and particulate compounds emissions than cities with a high wind speed in the atmosphere (about 88 polluted days vs. 65 polluted days exceeding PM$_{10}$ or ozone per year).

| Days exceeding limits set for PM$_{10}$ or ozone | Infected Individuals 19th March 2020 | Infected Individuals 6th April 2020 | Infected Individuals 26th April 2020 | Density inhabitants/ km$^2$ 2019 | Wind km/h Feb-Mar 2020 | Temperatur e °C Feb-Mar 2020 |
| Cities in regions with high wind speed in the atmosphere (> 9 km/h) | Arithmetic Mean | 64.85 | 252.48 | 1198.52 | 1826.19 | 1153.85 | 11.12 | 9.82 |
| | Std. Error of Mean | 6.93 | 40.91 | 176.32 | 290.02 | 303.74 | 0.58 | 0.54 |
| N=27 | | | | | | |

| Days exceeding limits set for PM$_{10}$ or ozone | Infected Individuals 19th March 2020 | Infected Individuals 6th April 2020 | Infected Individuals 26th April 2020 | Density inhabitants/ km$^2$ 2019 | Wind km/h Feb-Mar 2020 | Temperatur e °C Feb-Mar 2020 |
| Cities in regions with low wind speed in the atmosphere (≤ 9 km/h) | Arithmetic Mean | 87.89 | 850.32 | 2731.64 | 3963.86 | 1742.11 | 6.35 | 8.97 |
| | Std. Error of Mean | 8.32 | 209.62 | 565.33 | 830.65 | 340.18 | 0.55 | 0.27 |
| N=28 | | | | | | |

This preliminary result suggests that high intensity of wind speed in the atmosphere improves the dispersion of gaseous and particulate matters, and as a consequence, it mitigates, i.e. reduces, diffusion of COVID-19 infection in environment and society. In order to confirm this result, Table 2 considers air pollution and particulate compounds emissions in the atmosphere of cities: especially, cities with high air pollution and particulate compounds emissions in the atmosphere (>100 days exceeding limits set for PM$_{10}$ or ozone per year) and low wind speed, they have a very high level of infected individuals in March and April 2020, in an environment with high average density of population.
Table 2. Descriptive statistics of Italian provincial capitals according to air pollution and particulate compounds emissions in the atmosphere

| Cities with high air pollution and particulate compounds emissions in the atmosphere: | Days exceeding limits set for PM_{10} or ozone N=20 | Infected Individuals 19th March 2020 | Infected Individuals 6th April 2020 | Infected Individuals 26th April 2020 | Density inhabitants/km² 2019 | Wind km/h Feb-Mar 2020 | Temperature °C Feb-Mar 2020 |
|---|---|---|---|---|---|---|---|
| >100 days exceeding limits set for PM_{10} | 125.25 | 1102.00 | 3575.15 | 5293.10 | 1981.40 | 7.67 | 9.19 |
| Cities with low air pollution and particulate compounds emissions in the atmosphere: | Days exceeding limits set for PM_{10} or ozone N=35 | Infected Individuals 19th March 2020 | Infected Individuals 6th April 2020 | Infected Individuals 26th April 2020 | Density inhabitants/km² 2019 | Wind km/h Feb-Mar 2020 | Temperature °C Feb-Mar 2020 |
| ≤100 days exceeding limits set for PM_{10} | 48.77 | 245.31 | 1066.94 | 1555.23 | 1151.57 | 9.28 | 9.49 |

Table 3. Bivariate Correlation

| Cities in regions with high wind speed in the atmosphere (> 9 km/h) | Log Days exceeding limits set for PM_{10} or ozone 2018 | Log Infected Individuals 19th March, 2020 Pearson Correlation | Log Infected Individuals 6th April, 2020 Pearson Correlation | Log Infected Individuals 26th April, 2020 Pearson Correlation |
|---|---|---|---|---|
| Log Days exceeding limits set for PM_{10} or ozone 2018 | .68** | .88** | .80** |
| Log Infected Individuals 19th March, 2020 Pearson Correlation | .51** |
| Log Infected Individuals 6th April, 2020 Pearson Correlation | .96** |
| Log Infected Individuals 26th April, 2020 Pearson Correlation | .93** |

**Note:** **. Correlation is significant at the 0.01 level (2-tailed)

Table 3 shows that cities of regions with high and low wind speed, they have a high positive correlation (p-value<.01) between air pollution and particulate compounds emissions in the atmosphere and infected individuals of COVID-19 in March and April 2020.

Table 4. Parametric estimates of the relationship of Log Infected individuals on Log Air pollution and particulate compounds emissions in the atmosphere considering the groups of cities with high or low wind speed

| Cities in regions low wind speed in the atmosphere (≤9 km/h) | Explanatory variable: Log Days exceeding limits set for PM_{10} or ozone 2018 | Log Infected | Log Infected |
|---|---|---|---|
| Dependent Variable | Constant α | Coefficient β1 | R² (St. Err. of Estimate) |
| 6th April, 2020 | 3.62** | .88** | .26 (.92) |
| (St. Err.) | (.126) | (.29) | |
| R² (St. Err. of Estimate) | 9.28** |
| F | |

| Cities in regions high wind speed in the atmosphere (≥9 km/h) | Explanatory variable: Log Days exceeding limits set for PM_{10} or ozone 2018 | Log Infected | Log Infected |
|---|---|---|---|
| Dependent Variable | Constant α | Coefficient β1 | R² (St. Err. of Estimate) |
| 6th April, 2020 | 2.14* | 1.34*** | .44 (.74) |
| (St. Err.) | (1.05) | (.26) | |
| R² (St. Err. of Estimate) | 16.27*** |

**Note:** Explanatory variable: Log Days exceeding limits set for PM_{10} or ozone 2018; dependent variable Log infected individuals; *** p-value<0.001; ** p-value<0.01; * p-value<0.05

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Table 4 suggests that air pollution and particulate compounds emissions in the atmosphere explain the number of infected individuals of COVID-19. In particular,

- cities with low wind speed in the atmosphere, an increase of 1% of air pollution and particulate compounds emissions, measured with days exceeding limits set for PM$_{10}$, it increases the expected number of infected COVID-19 by about 0.88% (P<.01).

- cities with high wind speed in the atmosphere, an increase of 1% of air pollution and particulate compounds emissions, measured with days exceeding limits set for PM$_{10}$, it increases the expected number of infected COVID-19 by about 0.14% (P<.001).

Figure 1. Regression lines of Log Infected Individuals on Log Air pollution and particulate compounds emissions in the atmosphere according to wind speed of cities.

Note: This result suggests that diffusion of COVID-19 infection is higher in cities with low wind speed and moderate air pollution and particulate compounds emissions in the atmosphere. In order to confirm this result, table 6 considers cities with a high and low polluting industrialization.

Figure 1. shows a visual representation of regression lines that cities with low atmospheric circulation - wind speed, initially, they have a high number of total infected individuals driven by a moderate air pollution and particulate compounds emissions in the atmosphere.

Table 5. Parametric estimates of the relationship of Log Infected individuals on Log Density inhabitants/km$^2$ 2019, considering the groups of cities with high and low air pollution and particulate compounds emissions in the atmosphere.

| DEPENDENT VARIABLE | Cities with low air pollution and particulate compounds emissions | Cities with high air pollution and particulate compounds emissions |
|---------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| **Explanatory variable:** | Log Density inhabitants/km$^2$ 2019 | Log Density inhabitants/km$^2$ 2019 |
| loginfected 6th April, 2020 | 4.62*** (St. Err.) | 1.61 (St. Err.) |
| Constant $\alpha$ | (.76) | (1.52) |
| Coefficient $\beta$ | .32** (St. Err.) | .85*** (St. Err.) |
| $R^2$ (St. Err. of Estimate) | .18 (.78) | .48 (.75) |
| F | 7.42** | 16.63*** |

Note: Explanatory variable: log Density inhabitants/km$^2$ in 2019; dependent variable log infected individuals; *** p-value<0.001; ** p-value<0.01; * p-value<0.05

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Table 5 reveals that:

- In cities with low air pollution and particulate compounds emissions in the atmosphere, an increase of 1% of the density of population increases the expected number of infected individuals with COVID-19 by about 0.31% (p-value = .01).

- In cities with high air pollution and particulate compounds emissions in the atmosphere, an increase of 1% of the density of population increases the expected number of infected individuals by about 85% (P < .001).

Figure 2 shows regression lines on 6th April 2020, in the middle phase of COVID-19 outbreak in Italy: regions with an atmosphere rich of air pollutants, associated with a climatological factor of low wind speed, can support a stronger diffusion of COVID-19 infection.

In addition, if we consider regions with high/low air pollution and particulate compounds emissions in the atmosphere, using arithmetic mean of days exceeding limits set for PM10 or ozone of cities, the percentage of infected individuals and total deaths, weighted with population of these regions, reveals that about 74.50% of infected individuals and about 81% of total deaths in Italy because of COVID-19 infection are in regions with high air pollution and particulate compounds emissions in the atmosphere, cities located in hinterland zones (i.e. away from the coast, mostly those bordering large urban conurbations, such as Bergamo, Brescia and Cremona close to Milan in Lombardy region of North-West Italy), cities also having a low average intensity of wind speed and cities with a lower temperature.

Figure 2. Regression line of Log Infected people on Log population density inhabitants, considering the groups of cities with high or low air pollution and particulate compounds emissions in the atmosphere. Note: This result reveals that diffusion of COVID-19 is higher in cities with high Air pollution and particulate compounds emissions in the atmosphere.

4. Discussion

The current pandemic of Coronavirus disease and future epidemics similar to COVID-19 cannot be solved only with research and practice of medicine, immunology and microbiology but also with the development of environmental policy to reduce emission of particulate compounds, improving air quality and ecosystem. These findings here provide valuable...
insight into atmospheric-environmental factors that may accelerate the diffusion of COVID-19 and similar viral agents. The main results of the study, based on case study of COVID-19 outbreak in Italy, are cities with little wind, and frequently high levels of air pollution and particulate compounds emissions in the atmosphere — exceeding safe levels of ozone or particulate matter — had higher numbers of COVID-19 related deaths.

Considering the result just mentioned, the fundamental question is:

- what is the link between diffusion of COVID-19 infection, air pollution and particulate compounds emissions in the atmosphere and low atmospheric circulation with low wind speed?

Results suggest that, among Italian provincial capitals, the number of infected people is higher in cities with air pollution and particulate compounds emissions in the atmosphere, cities located in hinterland zones (i.e. away from the coast), cities having a low average intensity of wind speed and cities with a lower temperature. In particular, in hinterland cities (mostly those bordering large urban conurbations, such as Bergamo, Brescia, Lodi, close to Milan in Lombardy region of North Italy) with a high levels of air pollution and particulate compounds emissions in the atmosphere, coupled with low wind speed in the atmosphere, the average number of infected people in April 2020 more than doubled that of more windy cities. Therefore, cities in regions, with an atmosphere having a high intensity of wind speed, sustains clean days from air pollution and particulate compounds emissions, which current studies suggest is one of the drivers of the diffusion of Coronavirus infection. As a matter of fact, cities in hinterland zones (i.e. away from the coast) of Northern Italy with high air pollution and particulate compounds emissions, also having a low wind speed, have a stagnation of air pollution and particulate compounds in the atmosphere that can support diffusion of COVID-19 infection (Contini & Costabile, 2020; Conticini et al., 2020; Fattorini & Regoli, 2020). The implications for an environmental policy are clear: COVID-19 outbreak has low diffusion in cities of regions with low air pollution and particulate compounds emissions and atmosphere with a high circulation given by wind speed. Northern Italian regions and in particular hinterland cities, covered by the study, considering the structure of the atmosphere with low circulation given by low wind speed over time and space, as a consequence, in future should apply an environmental policy based on strategies of mitigation of air pollution and particulate compounds emissions, so that the accelerated transmission dynamics of infections similar to COVID-19 re not triggered.

In order to reinforce these conclusions with a perspective of environmental policies, Xu et al. (2020) found out the effect of moisture on explosive growth in fine particulate matter (PM), and propose a new approach for the simulation of fine PM growth and dissipation in ambient air. In particular, winds significantly aid the dissipation of fine PM, and high concentrations of fine PM only persisted for a very short time and dissipated after several hours. The role of climatological factors, such as wind speed and direction, temperature, and humidity are critical for urban ventilation and the pollutant concentration in the streets of cities (Yuan et al., 2020).
Hence, cities and regions should consider the benefit of a high atmospheric circulation with high wind speed wind that can increase the dispersion of air pollution and particulate compounds emissions and, as a consequence, reduce diffusion of viral infectivity with main public health benefits, as well as cities have to consider a pollution industrialization in areas with low wind speed that can increase stagnation of the air in the atmosphere with potential problems for public health in the presence of viral agents. Gu et al. (2020) argue that a strategy to enhance air quality in cities is improving urban ventilation: the ability of an urban area to dilute pollutants and heat by improving the exchange of air between areas within and above the urban canopy. Of course, urban ventilation is a function of a manifold urban geometry parameters, e.g., frontal area density, and plan area density and the aspect ratio of the urban morphology (Gu et al., 2020). Studies show that variations of building height have beneficial effects in terms of breathability levels, whereas larger aspect ratios of urban canyons can lead to high levels of pollutant concentrations inside the streets of cities. Hence, cities located in hinterland zones of the northern Italian region with low wind speed have an urban climatology and aspects of urban and regional topography that sustain the stagnation of air pollution and particulate compounds that can support the spread of viral infectivity in fall and winter season. These regions have to design environmental and industrial policies to reduce the level of air pollutants directed to reduce polluting industrialization and support a sustainable production with benefits for air quality and human health (Wang & Zhu, 2020). In fact, health and economic benefits associated with national and local reduction of air pollution are now rarely contested. Cui et al. (2020), based on a study in China, show that where reductions in ambient air pollution have avoided more than 2,300 premature deaths and more than 15,80 related morbidity cases in 2017, with a total of about US$ 318 million in economic benefits. In addition, these scholars argue that reduction of PM$_{2.5}$ concentrations to 15 μg/m$^3$ would result in reductions of 70% in total PM$_{2.5}$-related non-accidental mortality and 95% in total PM$_{2.5}$-related morbidity, with economic benefits of more than US$ 1,289.5 million. In short, environmental policies that improve air quality and reduce air pollution generate significant health, social and economic benefits in the ecosystem.

Overall, then, in order to prevent epidemics similar to COVID-19 and other infection, nations have, more and more, to apply an environmental and sustainable policy and technologies directed to reduce air pollution that improves public health of population and mitigates the negative effects of airborne viral diseases$^1$. A comprehensive environmental policy for a

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$^1$For studies about the interaction between science, technology and innovation, their sources, evolution, diffusion and impact on socioeconomic systems, see: Cavallo et al., 2014; Coccia, 1999, 2001, 2004, 2005, 2005a, b, c, 2006, 2007, 2008, 2009, 2009a,b,c; 2010, 2010a,b; 2012, 2012a,b; 2013; 2014, 2014a, b, c,d; 2015, 2015a, b; 2016, 2016a; 2017, 2017a, b, c, d, e, f, g, 2018, 2018a, b, c, d, e, f, g, h, i; 2019, 2019a, b, c, d, e, f, g, h, i, l, m; Coccia, 2020a, b, c, d, e, f, g, h, i, l, m; Coccia and Bellitto, 2018, Coccia and Cadario, 2018; Coccia et al.
sustainable development has to consider the urban climatology and atmosphere of regions with the study of climatic properties of urban areas and support a better air quality (Gu et al., 2020; Wang & Zhu, 2020).

5. Conclusions

The concentration in specific areas of a combination of atmosphere with low wind, specific urban climatology of hinterland cities, high Air pollution and particulate compounds emissions, aspects of regional topography and physical geography sustains, in fall and winter season, the stagnation of air pollution that has supported the spread of COVID-19 infection and likely in future of other infections (cf., Contini & Costabile, 2020; Conticini et al., 2020; Fattorini & Regoli, 2020). New findings here show that geo-environmental and atmospheric factors of hinterland zones with low wind may have accelerated the spread of COVID-19 in northern Italian cities, leading to a higher numbers of COVID-19 related infected individuals and deaths.

However, these conclusions are of course tentative because there are several challenges to such studies, particularly in real time because the sources can only capture certain aspects of the on-going complex relations between air pollution and particulate compounds emissions, atmospheric composition and impact, and diffusion of viral infectivity in ecosystem. This study therefore encourages further investigations on these aspects of the diffusion of COVID-19 outbreaks in regions that have a specific atmosphere composition and impact on environment to design appropriate environmental policies that are also main public health measure to reduce air pollution and control the spread of infection similar to COVID-19 (Ou et al., 2020). In short, in the presence of high air pollution and particulate compounds emissions and low wind speed in the atmosphere that can support diffusion of epidemics in environment, this study must conclude that a comprehensive strategy to prevent future epidemics similar to COVID-19 has also to be designed in terms of environmental science to improve air quality and human health.

To conclude, a proactive environmental strategy to help cope with future epidemics should concentrate on reducing levels of air pollution in hinterland and polluted cities. Therefore, such a strategy needs to take into account socioeconomic and environmental factors of affected regions, not only factors related to biology and medicine.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No funding was received for this study.

2015; Coccia and Finardi, 2012, 2013; Coccia et al., 2012; Coccia and Rolfo, 2008, 2009, 2010, 2013; Coccia and Wang, 2015, 2016; Coccia and Watts, 2020.
References

Cavallo, E., Ferrari E., Bollani, L., & Coccia M. (2014). Strategic management implications for the adoption of technological innovations in agricultural tractor: the role of scale factors and environmental attitude, *Technology Analysis & Strategic Management*, 26(7), 765-779. doi: 10.1080/09537325.2014.890706

Center for System Science and Engineering at Johns Hopkins 2020. Coronavirus COVID-19 Global Cases, accessed in 9th May 2020. [Retrieved from].

Cavallo, E., Ferrari E., Bollani, L., & Coccia M. (2014). Strategic management implications for the adoption of technological innovations in agricultural tractor: the role of scale factors and environmental attitude, *Technology Analysis & Strategic Management*, 26(7), 765-779. doi: 10.1080/09537325.2014.890706

Coccia, M. (2001). Satisfaction, work involvement and R&D performance. *International Journal of Human Resources Development and Management*, 1(2-3-4), 268-282. doi: 10.1504/IJHRDM.2001.001010

Coccia, M. (2003). Metrics of R&D performance and management of public research institute. *Proceedings of IEEE- IEMC 03*, Piscataway, pp.231-236.

Coccia, M. (2004). Spatial metrics of the technological transfer: analysis and strategic management. *Technology Analysis & Strategic Management*, 16(1), 31-52. doi: 10.1080/0953732032000175490

Coccia, M. (2005). Countrymetrics: valutazione della performance economica e tecnologica dei paesi e posizionamento dell’Italia, *Rivista Internazionale di Scienze Sociali*, CXIII(3), 377-412.

Coccia, M. (2005a). Metrics to measure the technology transfer absorption: analysis of the relationship between institutes and adopters in northern Italy. *International Journal of Technology Transfer and Commercialization*, 4(4), 462-486. doi: 10.1504/IJTTC.2005.006699

Coccia, M. (2005b). Technometrics: Origins, historical evolution and new direction, *Technological Forecasting & Social Change*, 72(8), 944-979. doi: 10.1016/j.techfore.2005.05.011

Coccia, M. (2005c). Economics of scientific research: origins, nature and structure, *Proceedings of Economic Society of Australia*.

Coccia, M. (2006). Classifications of innovations: survey and future directions. *Working Paper Ceris del Consiglio Nazionale delle Ricerche*, 8(2), 1-19. [Retrieved from].

Coccia, M. (2006a). Analysis and classification of public research institutes. *World Review of Science, Technology and Sustainable Development*, 3(1), 1-16.

Coccia, M. (2007). A new taxonomy of country performance and risk based on economic and technological indicators, *Journal of Applied Economics*, 10(1), 29-42.

Coccia, M. (2008). Science, funding and economic growth: analysis and science policy implications. *World Review of Science, Technology and Sustainable Development*, 5(1), 1-27. doi: 10.1504/WRSTSD.2008.01781

Coccia, M. (2008a). Spatial mobility of knowledge transfer and absorptive capacity: analysis and measurement of the impact within the geoeconomic space. *The Journal of Technology Transfer*, 33(1), 105-122. doi: 10.1007/s10961-007-9032-4

Coccia, M. (2008b). New organizational behaviour of public research institutions: Lessons learned from Italian case study. *International Journal of Business Innovation and Research*, 2(4), 402–419. doi: 10.1504/IJIBIR.2008.018589

Coccia, M. (2009). A new approach for measuring and analyzing patterns of regional economic growth: empirical analysis in Italy. *Italian Journal of Regional Science- Scienze Regionali*, 8(2), 71-95. doi: 10.3280/SCRE2009-002004

Coccia, M. (2009a). Measuring the impact of sustainable technological innovation, *International Journal of Technology Intelligence and Planning*, 5(3), 276-288. doi: 10.1504/IJTIP.2009.026749

Coccia, M. (2010). Public and private R&D investments as complementary inputs for productivity growth. *International Journal of Technology, Policy and Management*, 10(1/2), 73-91. doi: 10.1504/IJTPM.2010.032855

Coccia, M. (2010a). Foresight of technological determinants and primary energy resources of future economic long waves, *International Journal of Foresight and Innovation Policy*, 6(4), 225–232. doi: 10.1504/IJFIP.2010.037468
Coccia, M. (2010b). Energy metrics for driving competitiveness of countries: Energy weakness magnitude, GDP per barrel and barrels per capita. *Energy Policy*, 38(3), 1330-1339. doi: 10.1016/j.enpol.2009.11.011

Coccia, M. (2010c). Spatial patterns of technology transfer and measurement of its friction in the geo-economic space. *International Journal of Technology Transfer and Commercialisation*, 9(3), 255-267. doi: 10.1504/IJITTC.2010.030214

Coccia, M. (2010d). The asymmetric path of economic long waves, *Technological Forecasting & Social Change*, 77(5), 730-738. doi: 10.1016/j.techfore.2010.02.003

Coccia, M. (2010e). Democratization is the driving force for technological and economic change, *Technological Forecasting & Social Change*, 77(2), 248-264. doi: 10.1016/j.techfore.2009.06.007

Coccia, M. (2011). The interaction between public and private R&D expenditure and national productivity. *Prometheus-Critical Studies in Innovation*, 29(2), 121-130. doi: 10.1080/08109028.2011.601079

Coccia, M. (2012). Political economy of R&D to support the modern competitiveness of nations and determinants of economic optimization and inertia, *Technovation*, 32(6), 370-379. doi: 10.1016/j.technovation.2012.03.005

Coccia, M. (2012a). Evolutionary trajectories of the nanotechnology research across worldwide economic players. *Technology Analysis & Strategic Management*, 24(10), 1029-1050. doi: 10.1080/09537325.2012.705117

Coccia, M. (2012b). Evolutionary growth of knowledge in path-breaking targeted therapies for lung cancer: radical innovations and structure of the new technological paradigm. *International Journal of Behavioural and Healthcare Research*, 3(3-4), 273-290. doi: 10.1504/IJBHR.2012.051406

Coccia, M. (2012c). Converging genetics, genomics and nanotechnologies for groundbreaking pathways in biomedicine and nanomedicine. *International Journal of Healthcare Technology and Management*, 14(3), 194-197. doi: 10.1504/IJHTM.2012.050616

Coccia, M. (2012d). Driving forces of technological change in medicine: Radical innovations induced by side effects and their impact on society and healthcare. *Technology in Society*, 34(4), 271-283. doi: 10.1016/j.techsoc.2012.06.002

Coccia, M. (2013). What are the likely interactions among innovation, government debt, and employment? *Innovation: The European Journal of Social Science Research*, 26(4), 456-471. doi: 10.1080/13511610.2013.863704

Coccia, M. (2013a). The effect of country wealth on incidence of breast cancer. *Breast Cancer Research and Treatment*, 141(2), 225-229. doi: 10.1007/s10549-013-2683-y

Coccia, M. (2014). Path-breaking target therapies for lung cancer and a far-sighted health policy to support clinical and cost effectiveness. *Health Policy and Technology*, 1(3), 74-82. doi: 10.1016/j.hlpt.2013.09.007

Coccia, M. (2014a). Emerging technological trajectories of tissue engineering and the critical directions in cartilage regenerative medicine. *Int. J. Healthcare Technology and Management*, 14(3), 194-208. doi: 10.1504/IJHTM.2014.064247

Coccia, M. (2014b). Converging scientific fields and new technological paradigms as main drivers of the division of scientific labour in drug discovery process: the effects on strategic management of the R&D corporate change. *Technology Analysis & Strategic Management*, 26(7), 733-749. doi: 10.1080/09537325.2014.882501

Coccia, M. (2014c). Driving forces of technological change: The relation between population growth and technological innovation-Analyis of the optimal interaction across countries, *Technological Forecasting & Social Change*, 82(2), 52-65. doi: 10.1016/j.techfore.2013.06.001

Coccia, M. (2014). Socio-cultural origins of the patterns of technological innovation: What is the likely interaction among religious culture, religious plurality and innovation? Towards a theory of socio-cultural drivers of the patterns of technological innovation, *Technology in Society*, 36(1), 13-25. doi: 10.23760/2421-7158.2017.004

Coccia, M. (2014e). Religious culture, democratisation and patterns of technological innovation. *International Journal of Sustainable Society*, 6(4), 397-418. doi: 10.1504/IJSSOC.2014.066771

M. Coccia, TER, 8(1), 2021, p.14-29.
Coccia, M. (2014f). Structure and organisational behaviour of public research institutions under unstable growth of human resources, *Int. J. Services Technology and Management*, 20(4/5/6), 251-266. doi. 10.1504/IJSTM.2014.068857

Coccia, M. (2014g). Steel market and global trends of leading geo-economic players. *International Journal of Trade and Global Markets*, 7(1), 36-52. doi. 10.1504/IJTGM.2014.058714

Coccia, M. (2015). The Nexus between technological performances of countries and incidence of cancers in society. *Technology in Society*, 42, 61-70. doi. 10.1016/j.techsoc.2015.02.003

Coccia, M. (2015a). Patterns of innovative outputs across climate zones: the geography of innovation, *Prometheus. Critical Studies in Innovation*, 33(2), 165-186. doi. 10.1080/08109028.2015.1095979

Coccia, M. (2015b). General sources of general purpose technologies in complex societies: Theory of global leadership-driven innovation, warfare and human development, *Technology in Society*, 42, 199-226. doi. 10.1016/j.techsoc.2015.05.008

Coccia, M. (2015c). Spatial relation between geo-climate zones and technological outputs to explain the evolution of technology. *Int. J. Transitions and Innovation Systems*, 4(1-2), 5-21. doi. 10.1504/IJTIS.2015.074642

Coccia, M. (2015d). Technological paradigms and trajectories as determinants of the R&D corporate change in drug discovery industry. *International Journal Knowledge and Learning*, 10(1), 29-43. doi. 10.1504/IJKL.2015.071052

Coccia, M. (2016). Asymmetric paths of public debts and of general government deficits across countries within and outside the European monetary unification and economic policy of debt dissolution. *The Journal of Economic Asymmetries*, 15, 17-31. doi. 10.1016/j.jeca.2016.10.003

Coccia, M. (2016a). Radical innovations as drivers of breakthroughs: characteristics and properties of the management of technology leading to superior organizational performance in the discovery process of R&D labs. *Technology Analysis & Strategic Management*, 28(4), 381-395. doi. 10.1080/09537325.2015.1095287

Coccia, M. (2016). Problem-driven innovations in drug discovery: co-evolution of radical innovation with the evolution of problems, *Health Policy and Technology*, 5(2), 143-155. doi. 10.1016/j.hlpt.2016.02.003

Coccia, M. (2016c). The relation between price setting in markets and asymmetries of systems of measurement of goods. *The Journal of Economic Asymmetries*, 14(B), 168-178. doi. 10.1016/j.jeca.2016.06.001

Coccia, M. (2017). The source and nature of general purpose technologies for supporting next K-waves: Global leadership and the case study of the U.S. Navy’s Mobile User Objective System, *Technological Forecasting and Social Change*, 116, 331-339. doi. 10.1016/j.techfore.2016.05.019

Coccia, M. (2017a). Optimization in R&D intensity and tax on corporate profits for supporting labor productivity of nations. *The Journal of Technology Transfer*, doi. 10.1007/s10961-017-9572-1

Coccia, M. (2017b). Varieties of capitalism’s theory of innovation and a conceptual integration with leadership-oriented executives: the relation between typologies of executive, technological and socioeconomic performances. *Int. J. Public Sector Performance Management*, 3(2), 148-168. doi. 10.1504/IJPSPM.2017.084672

Coccia, M. (2017c). Sources of disruptive technologies for industrial change. *L’industria – rivista di Economia e Politica industriale*, 38(1), 97-120.

Coccia, M. (2017d). Sources of technological innovation: Radical and incremental innovation problem-driven to support competitive advantage of firms. *Technology Analysis & Strategic Management*, 29(9), 1048-1061. doi. 10.1080/09537325.2016.1268682

Coccia, M. (2017e). A Theory of general causes of violent crime: Homicides, income inequality and deficiencies of the heat hypothesis and of the model of CLASH, *Aggression and Violent Behavior*, 37, 190-200. doi. 10.1016/j.avb.2017.10.005

Coccia, M. (2017f). New directions in measurement of economic growth, development and under development, *Journal of Economics and Political Economy*, 4(4), 382-395.
Coccia, M. (2017g). Disruptive firms and industrial change, *Journal of Economic and Social Thought*, 4(4), 437-450.

Coccia, M. (2017h). The Fishbone diagram to identify, systematize and analyze the sources of general purpose Technologies, *Journal of Social and Administrative Sciences*, 4(4), 291-303.

Coccia, M. (2018). A theory of the general causes of long waves: War, general purpose technologies, and economic change. *Technological Forecasting & Social Change*, 128, 287-295. 10.1016/j.techfore.2017.11.013

Coccia, M. (2018a). The relation between terrorism and high population growth, *Journal of Economics and Political Economy*, 5(1), 84-104.

Coccia, M. (2018c). Violent crime driven by income inequality between countries, *Turkish Economic Review*, 5(1), 33-55.

Coccia, M. (2018d). The origins of the economics of innovation, *Journal of Economic and Social Thought*, 5(1), 9-28.

Coccia, M. (2018e). Theorem of not independence of any technological innovation, *Journal of Economics Bibliography*, 5(1), 29-35.

Coccia, M., & Bellitto, M. (2018). Human progress and its socioeconomic effects in society, *Journal of Economic and Social Thought*, 5(2), 160-178.

Coccia, M., & Igor, M. (2018). Rewards in public administration: a proposed classification, *Journal of Social and Administrative Sciences*, 5(2), 68-80.

Coccia, M., & Bozeman, B. (2016). Allometric models to measure and analyze the evolution of international research collaboration. *Scientometrics*, 108(3), 1065-1084. doi. 10.1007/s11192-016-2027-x

Coccia, M., Falavigna, G., & Manello, A. 2015. The impact of hybrid public and market-oriented financing mechanisms on scientific portfolio and performances of public research labs: a scientometric analysis. *Scientometrics*, 102(1), 151-168. doi. 10.1007/s11192-014-1427-z

Coccia, M., & Rolfo, S. (2000). Ricerca pubblica e trasferimento tecnologico: il caso della regione Piemonte. In S. Rolfo (ed), *Innovazione e piccole imprese in Piemonte*, Franco Angeli Editore, Milano.

Coccia, M., & Rolfo, S. (2002). Technology transfer analysis in the Italian national research council, *Technovation - The International Journal of Technological Innovation and Entrepreneurship*, 22(5), 291-299. doi. 10.1016/S0166-4972(01)00018-9

Coccia, M., & Rolfo, S. (2007). How research policy changes can affect the organization and productivity of public research institutes, *Journal of Comparative Policy Analysis, Research and Practice*, 9(3) 215-233. doi. 10.1080/13876980701494624

Coccia, M., & Rolfo, S. (2010). New entrepreneurial behaviour of public research organizations: opportunities and threats of technological services supply, *International Journal of Services Technology and Management*, 13(1-2), 134-151. doi. 10.1504/IJSTM.2010.029674

M. Coccia, TER, 8(1), 2021, p.14-29.
Coccia, M., & Rolfo, S. (2013). Human resource management and organizational behavior of public research institutions, *International Journal of Public Administration*, 36(4), 256-268. doi. 10.1080/01900692.2012.756889

Coccia, M., & Rolfo, S. (2009). Project management in public research organization: Strategic change in complex scenarios. *International Journal of Project Organisation and Management*, 1(3), 235-252. doi. 10.1504/IJPOM.2009.027537

Coccia, M., & Wang, L. (2015). Path-breaking directions of nanotechnology-based chemotherapy and molecular cancer therapy, *Technological Forecasting and Social Change*, 94, 155-169. doi. 10.1016/j.techfore.2014.09.007

Coccia, M., & Wang, L. (2016). Evolution and convergence of the patterns of international scientific collaboration. *Proceedings of the National Academy of Sciences of the United States of America*, 113(8), 2057-2061. doi. 10.1073/pnas.1510820113

Conticini E., Frediani B., & Caro D. (2020). Can atmospheric pollution be considered a co-factor in extremely high level of SARS-CoV-2 lethality in Northern Italy? *Environmental Pollution*, 261,114465. doi. 10.1016/j.envpol.2020.114465

Contini, D., & Costabile, F. (2020). Does Air Pollution Influence COVID-19 Outbreaks? *Atmosphere*, 11, 377.

Cui L., Zhou J., Peng X., Ruan S., & Zhang Y. (2020). Analyses of air pollution control measures and co-benefits in the heavily air-polluted Jinan city of China, 2013-2017. *Sci Rep*. 10(1), 5423. doi. 10.1038/s41598-020-62475-0

Dantas G., Bruno, S., França, B.B., Cleyton, M., & Arbilla, G. (2020). The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil, *Science of The Total Environment*, 729, 139085. doi. 10.1016/j.scitotenv.2020.139085

Fattorini D., & Regoli F. (2020). Role of the chronic air pollution levels in the Covid-19 outbreak risk in Italy, *Environmental Pollution*, 264, 114732. doi. 10.1016/j.envpol.2020.114732

Frontera A., Martin, C., Vlachos, K., & Sgubin, G. (2020). Regional air pollution persistence links to COVID-19 infection zoning, *J Infect*. 10, 35-46. doi. 10.1016/j.jinf.2020.03.045

Gu K., Fang, Y., Qian, Z., Sun, Z., & Wang, A. (2020). Spatial planning for urban ventilation corridors by urban climatology, *Ecosystem Health and Sustainability*, 6(1), 1747946. doi. 10.1080/20964129.2020.1747946

Il meteo (2020). Medie e totali mensili. Accessed March 2020. [Retrieved from].

ISTAT (2020). The Italian National Institute of Statistics-Popolazione residente al 1 gennaio, [Retrieved from].

Lab24 2020. Coronavirus in Italia, i dati e la mappa. Il Sole24ORE. Accessed, 9 May, 2020. [Retrieved from].

Legambiente (2019). Mal’aria 2019, il rapporto annuale sull’inquinamento atmosferico nelle città italiane. Accessed March 2020. [Retrieved from].

Ministero della Salute (2020). Covid-19 - Situazione in Italia. Accessed April 2020. [Retrieved from].

Ogen, Y. (2020). Assessing nitrogen dioxide (NO2) levels as a contributing factor to coronavirus (COVID-19) fatality, *Science of The Total Environment*, 726, 138605. doi. 10.1016/j.scitotenv.2020.138605

Ou Y., West, J., Smith, S., Nolte, C., & Loughlin, D. (2020). Air Pollution Control Strategies Directly Limiting National Health Damages in the U.S. *Nature Communications*, 11, 957. doi. 10.1038/s41467-020-14783-2

Saadat S., Rawtani, D., Hussain, C.M. (2020). Environmental perspective of COVID-19, *Science of The Total Environment*, 728, 138870. doi. 10.1016/j.scitotenv.2020.138870

van Doremalen N., Bushmaker T., Morris D.H., Holbrook M.G., Gamble A., Williamson B.N., Tamin A., Harcourt J.L., Thornburg N.J., Gerber S.I., Lloyd-Smith J.O., de Wit E., Munster V.J. (2020). Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *Nature Communications*, 11, 957. doi. 10.1038/s41467-020-14783-2

Wang Q., & Su M. (2020). A preliminary assessment of the impact of COVID-19 on environment – A case study of China, *Science of The Total Environment*, 728, 138915. doi. 10.1016/j.scitotenv.2020.138915

M. Coccia, TER, 8(1), 2021, p.14-29.
Wang Z., & Yongfeng, Z. (2020). Do energy technology innovations contribute to CO2 emissions abatement? A spatial perspective, *Science of The Total Environment*, 726, 138574. doi. 10.1016/j.scitotenv.2020.138574

Xu J., Fahua Zhu, Sheng Wang, Xiuyong Zhao, Ming Zhang, Xinlei Ge, Junfeng Wang, Wenxin Tian, Liwen Wang, Liu Yang, Li Ding, Xiaobo Lu, Xinxin Chen, Youfei Zheng, Zhaobing Guo (2020). A preliminary study on wind tunnel simulations of the explosive growth and dissipation of fine particulate matter in ambient air, *Atmospheric Research*, 235, 104635. doi. 10.1016/j.atmosres.2019.104635

Yuan M., Song, Y., Huang, Y., Shen, H., & Li, T. (2019). Exploring the Association between the Built Environment and Remotely Sensed PM$_{2.5}$ Concentrations in Urban Areas. *Journal of Cleaner Production*, 220, 1014–1023. doi. 10.1016/j.jclepro.2019.02.236

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