ppi 201502ZU4659
Esta publicación científica en formato digital es continuidad de la revista impresa
ISSN 0254 -0770 / e-ISSN 2477-9377 / Depósito legal pp 197802ZU38

Dr. Ignacio Rodríguez Iturbe - Zuliano ilustre
Ingeniero civil, hidrólogo, profesor universitario, doctor honoris causa de la Universidad del Zulia, epónimo de la orden al mérito Dr. Ignacio Rodríguez Iturbe, ciudadano ejemplar con numerosos premios nacionales e internacionales.

REVISTA TÉCNICA

DE LA FACULTAD DE INGENIERÍA

Una Revista Internacional Arbitrada que está indizada en las publicaciones de referencia y comentarios:

- REDALYC
- REDIB
- SCIELO
- DRJI
- INDEX COPERNICUS INTERNATIONAL
- LATINDEX
- DOAJ
- REVENCYT
- CHEMICAL ABSTRACT
- MIAR
- AEROSPACE DATABASE
- CIVIL ENGINEERING ABTRACTS
- METADEX
- COMMUNICATION ABSTRACTS
- ZENTRALBLATT MATH, ZBMATH
- ACTUALIDAD IBEROAMERICANA
- BIBLAT
- PERIODICA

UNIVERSIDAD DEL ZULIA

VOLUMEN 46 EDICIÓN CONTINUA AÑO 2023

Analysis on Air Pollution in South America during the Propagation of COVID-19

Walter José Martínez Burgos[1], Josilene Lima Serra[2], Alexander Parody Muñoz[3*], Leonardo Wedderhoff Herrmann[1], Euler Gallego-Cartagena[4] Carlos D. Paternina-Arboleda[5], Vanete Thomaz Soccol[1], Vera Judith Santiago Martínez[3], Carlos Ricardo Soccol[1]

[1]Programa de Ingeniería de Bioprocesos y Biotecnología, Universidade Federal do Paraná-Campus Centro politécnico, Avenida Coronel Francisco H. dos Santos, 100, Jardim das Américas, Curitiba, Brasil.

[2]Instituto Federal de Educação Ciência e Tecnologia do Maranhão. São Luís, Maranhão, Brasil.

[3]Programa de Ingeniería Industrial, Facultad de Ingeniería, Universidad Libre de Colombia, Seccional Barranquilla, Sede Centro Carrera 46 No. 48-170 Barranquilla, Colombia.

[4]Programa de Administración Ambiental e Ingeniería Ambiental, Departamento de Civil y Ambiental, Universidad de la Costa, Calle 58 #55-66, 080002, Barranquilla, Colombia.

[5]Department of Management Information Systems, San Diego State University, California, United States.

*Autor de correspondencia: alexandere.parodym@unilibre.edu.co

https://doi.org/10.22209/rt.v46a12

Recepción: 28 de febrero de 2022 | Aceptación: 11 de diciembre de 2023 | Publicación: 13 de diciembre de 2023

Abstract

The global pandemic due to the SARS-CoV-2 Coronavirus has caused significant impact on various sectors of society, e.g., health, science, and economy, with a remarkable change in environmental aspects. The present study focused on an analysis of the spread of COVID-19 in South America, highlighting the impacts of lockdown policies on the air quality in the main cities of ten countries during the pandemics, furthermore, through simple regression statistical models, the behavior of accumulated daily cases of COVID-19 in 13 countries was characterized. The lockdown strategy was one of the first measures adopted by the World Health Organization (WHO) to control the spread of the coronavirus, significantly reducing traffic and industrial activities. This measure has surprisingly improved the air quality in four of the 13 South American cities studied, e.g., Guarulhos (Brazil), Santiago de Chile (Chile), Bogota (Colombia), and Lima (Peru), with reductions in PM2.5, PM10, and ozone (O3). The propagation behavior of COVID-19 in South America and the environmental impact analyses provided in this paper demonstrate the intense effect of commercial and industrial activities and can be used to subsidize future reductions in pollution and disease contamination.

Keywords: air pollution; environment; Coronavirus; public health.

Análisis de la Contaminación Atmosférica en Sudamérica durante la Propagación de COVID-19

Resumen

La pandemia mundial causada por el coronavirus SARS-CoV-2 originó un impacto significativo en varios sectores de la sociedad, como por ejemplo: la salud, la ciencia y la economía, y sobre todo un cambio notable en los aspectos ambientales. El presente estudio se centró en un análisis sobre la propagación del COVID-19 en Sudamérica, destacando los impactos de las políticas de bloqueo en la calidad del aire de las principales ciudades de 13 países durante la pandemia; además, por medio de modelos estadísticos de regresión simple se caracterizó el comportamiento de los casos acumulados diarios de Covid-19 en los 13 países analizados. La estrategia de cierre fue una de las primeras medidas adoptadas por la Organización Mundial de la Salud (OMS) para controlar la propagación del coronavirus, reduciendo significativamente el tráfico y las actividades industriales. Esta medida demostró mejorar sorprendentemente la calidad del aire en cuatro de las 13 ciudades sudamericanas estudiadas, a saber: Guarulhos (Brasil), Santiago de Chile (Chile), Bogotá (Colombia) y Lima (Perú); con reducciones de PM2,5, PM10 y ozono (O3). El comportamiento de la propagación del COVID-19 en Sudamérica y los análisis de impacto ambiental proporcionados en este trabajo demuestran el intenso efecto de las actividades comerciales e industriales, y pueden ser utilizados para subvencionar futuras reducciones de la contaminación y de las enfermedades.

Palabras clave: ambiente; contaminación atmosférica; coronavirus; salud pública.

Análise da poluição atmosférica na América do Sul durante a propagação da COVID-19

Resumo

A pandemia global causada pelo coronavírus SARS-CoV-2 teve um impacto significativo em vários setores da sociedade, incluindo saúde, ciência, economia e, principalmente, uma notável mudança nos aspectos ambientais. Este estudo focou na análise da propagação da COVID-19 na América do Sul, destacando os impactos das políticas de lockdown na qualidade do ar das principais cidades de 13 países durante a pandemia. Além disso, utilizando modelos estatísticos de regressão simples, caracterizamos o comportamento dos casos diários acumulados de Covid-19 nos 13 países analisados. A estratégia de fechamento foi uma das primeiras medidas adotadas pela Organização Mundial da Saúde (OMS) para controlar a propagação do coronavírus, resultando em uma redução significativa do tráfego e das atividades industriais. Essa medida melhorou significativamente a qualidade do ar em quatro das 13 cidades sul-americanas estudadas, a saber: Guarulhos (Brasil), Santiago de Chile (Chile), Bogotá (Colômbia) e Lima (Peru); com reduções de PM2,5, PM10 e ozônio (O3). Os padrões observados na propagação da COVID-19 na América do Sul e as analyses de impacto ambiental fornecidas neste estudo demonstram o impacto significativo das atividades comerciais e industriais, que poderiam orientar estratégias futuras para reduzir a poluição e os problemas de saúde associados.

Palavras-chave: atmosfera; contaminação atmosferica; coronavírus; saúde pública.

Introduction

The Severe Acute Respiratory Syndrome 2 virus, SARS-CoV-2, is responsible for a major global pandemic that caused the coronavirus disease, beginning in 2019 (COVID-19). The novel coronavirus was first detected in a human host in Wuhan, Hubei Province, China, on December 12, 2019, from where it spread worldwide in at least three months. The COVID-19 virus is highly transmissible via droplets or direct contact through human-to-human interaction. To date (December 14, 2021), there were 270,031,622 confirmed cases and 5,310,502 deaths worldwide. The country with the highest number of confirmed cases is the United States of America (World Health Organization, 2021a). Focusing on the southern part of the American continent, regional divisions constitute twelve countries and six regions politically connected to France, the Netherlands, and the United Kingdom (Figure 1). Among South American countries, Brazil is the most affected by the COVID-19 disease and the third with the highest number of confirmed cases worldwide (World Health Organization, 2021a).

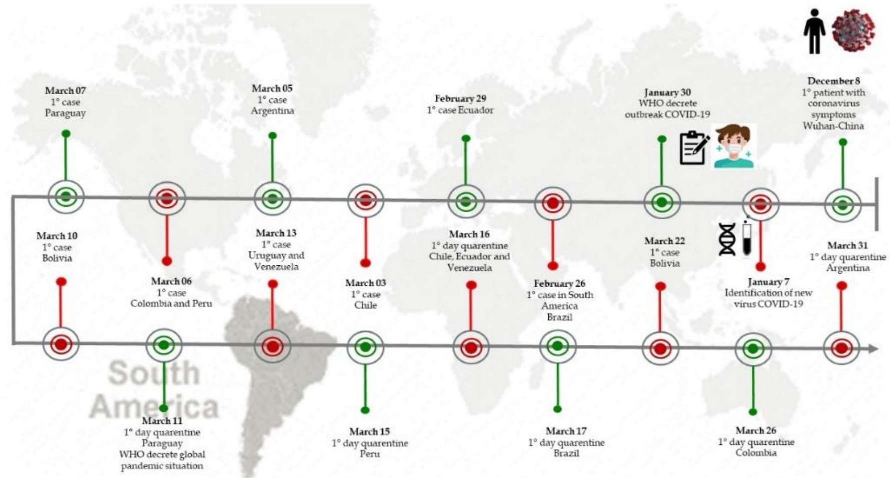


Figure 1. Propagation timeline of the COVID-19 disease from China to South America and adaptation of the lockdown days.

South American countries such as Brazil, Chile, and Colombia show some of the most urbanized regions in the world, considerably contributing to air pollution due to economic and industrial growth. In this scenario, the negative relationship between air pollution and human health has been under discussion by the scientific community for decades and represents a major risk factor responsible for many diseases and deaths. According to the WHO, a high level of air pollution increases the risk of conditions such as heart disease, stroke, chronic obstructive pulmonary disease, cancer, and pneumonia (Faiz et al., 1995; Bell et al., 2006; World Health Organization, 2021b). The severity of COVID-19 infection in major cities is closely related to air pollution. Specific areas of India, China, Italy, Russia, Chile, and Qatar show a positive correlation between high rates of air pollution, indicated by nitrogen dioxide (NO2), particulate matter with less than 2.5 micrometers (PM2.5), and COVID-19 infection. It has also been associated with the overexpression of the angiotensin-converting enzyme 2 (ACE-2) on epithelial cell surfaces of the respiratory tract (Paital and Agrawal, 2021).

According to many studies, the establishment of lockdown policies has had a positive effect on air quality (Collivignarelli et al., 2020; Dantas et al., 2020; Paital and Agrawal, 2021). In Latin America, the human activity, vehicle traffic, and industrial activities contributed to significantly reducing air-pollutant particles and gases such as PM2.5, particulate matter with less than 10 micrometers (PM10), carbon monoxide (CO), and nitrogen oxides (NOx), in addition to increasing ozone rates (Collivignarelli et al., 2020; Dantas et al., 2020). From this perspective, aiming to analyze the propagation of COVID-19 in South America and correlate it with air pollution, this study searched for data on air pollutants between 2019 and 2020, including the PM2.5, PM10, NO2, SO2, CO, and O3 factors.

Materials and Methods

Air pollution data collection

In this study was analyzed the major cities of eight South American countries (13): Buenos Aires (Argentina), La Paz (Bolivia), Guarulhos (Brazil), Campinas (Brazil), Santiago (Chile), Curicó (Chile), Bogotá (Colombia), Medellín (Colombia), Quito (Ecuador), Cuenca (Ecuador), Lima (Peru), Colón (Uruguay), and Montevideo (Uruguay). The number of COVID-19 cases was obtained from the online database of the WHO (World Health Organization, 2021a). The range established for data collection spanned from the first day of COVID-19 detection in each country to 30 days after detection from March 2020 to June 2021. This period was selected to analyze the air quality before and after COVID-19 was characterized as a pandemic. Air quality was analyzed according to data available in the databases of the Ministries of the Environment of each South American country between March 2019 and September 2020. The environmental variables used were PM2.5, PM10, CO, NO2, SO2, and O3.

Air pollution statistical analysis

Simple regression models were generated for the statistical analysis. The independent or explanatory variable referred to the number of days elapsed since the first report of a COVID-19 case. The dependent variable referred to the number of accumulated cases of COVID-19 contagion. The statistical software Statgraphics XVI (Centurion) was used in the analyses, which allows simultaneously contrasting 27 different regression models and choosing the model with the highest percentage of explanation for the dependent variable (R2). Each model was generated per country, and a model quality evaluation was applied to assess the homoscedasticity of forecast errors variance generated by the model, the average forecast error, and normality in the behavior of forecast errors.

Results and Discussion

Behavior and propagation of COVID-19 in South America

COVID-19 disease is a major health problem that negatively affects the global economy (Zhou *et al.*, 2020b; Zhu *et al.*, 2020) and spread all around the world. Until January 15, 2021, only a few countries had not officially reported any COVID-19 cases, *e.g.*, the Republic of Palau, the Republic of Kiribati, Vanuatu, and North Korea (World Health Organization, 2021a), while the rest of the world had reported approximately 100 million cases and around 2 million deaths (World Health Organization, 2021a). In South America, the first case was reported in Brazil on February 26, 2020, and the last countries to report their first cases were Uruguay and Venezuela, both on March 13, 2020. However, one of the characteristics of the SARS-CoV-2 virus is that it is highly contagious (Wang *et al.*, 2020; Zaconeta *et al.*, 2020) or, in other words, that it spreads quickly. For example, during May, September (2020), and January (2021), around 1, 11, and 14 million positive cases of COVID-19 were reported, respectively (World Health Organization, 2021a), whereas the first peak of the pandemic was reported between June and August.

The spread of COVID-19 around the world occurred in three phases, from China to South America, according to different regions (Figure 1). First, in late December 2019, the highest contamination focus was in Asia, with an epicenter in China. The second phase occurred in Europe on January 24, 2020, when the first cases were confirmed in that continent. Italy and Spain were the first affected countries, with higher numbers of cases between March and April. However, on September 22, 2020, Russia (1,109,595 cases), France (458,061 cases), and the United Kingdom (398,625 cases) surpassed the numbers of confirmed COVID-19 cases. The third phase occurred in America on January 21, 2020, with the first confirmed case in the United States of America and an exponential contamination growth curve in March. In Latin America, the first case was detected in Brazil (February 26), the country with the highest number of COVID-19 cases (4,558,068), followed by Peru (772,896) and Colombia (770,435) (World Health Organization, 2021a). Additionally, Brazil also reported a new virus variant, the Gamma variant, in November 2020, generating great concern (World Health Organization, 2021a).

On January 30, 2020, the WHO determined that the COVID-19 outbreak must be considered a Public Health Emergency of International Importance and recommended quarantine as a preventive measure, although attributing to each country the autonomy to adhere to adequate preventive measures. On March 11, 2020, with the increase in the severity and number of cases, the WHO announced a global pandemic status for COVID-19 (Pan American Health Organization and World Health Organization, 2020). In South America, chronologically, Paraguay was the first country to establish a lockdown policy, four days after detecting the first case of COVID-19. Uruguay was the country that had the fastest response, establishing the lockdown right after the first confirmed case. On the other hand, Argentina had the slowest response, adhering to this policy after 26 days. It should be noted that Uruguay and Paraguay were the countries with the lowest number of new cases after 100 days from the first detection. In contrast, Brazil was the Latin America country that reported the highest number of cases after 100 days from the first detection. However, the strategies adopted to control virus transmission in each country (mainly the use of masks and lockdown) and their infrastructure were determinants for the increase in the number of cases. Masks were an important preventive measure adopted during this period. An initial study reported that oral swab samples from patients infected with COVID-19 indicated a positive result for SARS-CoV-2 by qPCR and conventional PCR. These findings were the first evidence that the virus could be transmitted by air (Zhou *et al.*, 2020a). The readiness in which countries approved and registered diagnostic tests also influenced the correct detection of the infected and their accountability in global statistics (Vedova-Costa *et al.*, 2021).

In past human infection outbreaks, the transmission usually occurs first from animals to humans and later from humans to humans. The coronaviruses are largely found in animals such as cattle, dogs, bats, equines, and others. The first human case of COVID-19 was identified on December 12, 2019, in Wuhan City, Hubei Province, China. A cluster of patients with similar symptoms was identified at a seafood wholesale and live animals marketplace in the city (Rahman *et al*., 2020). In January 2020, the complete genome of SARS-CoV-2, isolated from a patient that worked at the Wuhan seafood market, was sequenced (29,903 nucleotides) and closely related to a group of coronaviruses found in bats throughout China (GenBank accession number MG772933). Another study also sequenced the complete genome of five samples isolated from patients, which were 96 % identical to the whole-genome level of a bat coronavirus, hypothetically considered to be the initial point of contamination of COVID-19 (Wu *et al*., 2020; Zhou *et al*., 2020b). The infection by the COVID-19 virus can be either asymptomatic or symptomatic, the latter leading to severe symptoms and potentially causing death. The disease develops in three stages: the early stage from 7 to 10 days, when there is a high viral load in the respiratory tract, fever (above 37.6 °C), diarrhea, and dry cough; the second stage, when pulmonary symptoms are observed, *e.g*., hypoxia; and the third stage, the hyperinflammation phase, when there is a high risk of thrombotic and embolic events due to the procoagulant state (Pericàs *et al*., 2020).

The second peak of the pandemic occurred from December 2020 to January 2021 and was characterized by an intense increase of positive cases. Brazil and Colombia reported the highest numbers of positive cases per day, with 87,843 and 17,576 cases, respectively. Uruguay reached its first epidemiological peak between December (2020) and January (2021). Among the countries with the highest numbers of reported cases, Brazil, Argentina, and Colombia corresponded to 59, 12.5, and 11.7 % of total cases, respectively. In contrast, the countries with the lowest number of cases are Venezuela and Uruguay, with 0.72 and 0.45 %, respectively (World Health Organization, 2021a). Rapid COVID-19 dissemination was observed one year after the disease was characterized as a global pandemic (Figure 2). In South America, Brazil stood out with an expressive number of confirmed COVID-19 cases, increasing from 5,385 cases in April 2020 to approximately 18 million in June 2021, proportional to its large population (World Health Organization, 2021a).

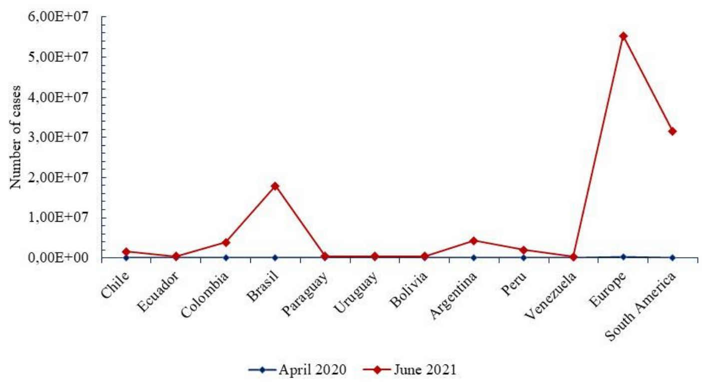


Figure 2. Number of COVID-19 cases in Europe and South America (World Health Organization, 2021a).

By considering other aspects of the disease, around 800 thousand sequences for SARS-CoV-2 have been deposited worldwide. In South America, only 879 sequences have been deposited. The main depositors are Chile, Brazil, and Peru with 43.6, 31.5, and 15.9 %, respectively, corresponding to 91.0 % of the total (Table 1).

Table 1. Total SARS-CoV-2 sequences deposited in the National Center for Biotechnology Information (National Library of Medicine, 2021).

Localization	Total sequences	South America	Total sequences
Africa	1,934	Brazil	277
Asia	5,680	Chile	383
Europe	438,222	Colombia	2
North America	351,479	Ecuador	4
Oceania	13,933	Peru	140
South America	879	Uruguay	10
		Venezuela	20
		Argentina	43
Total	**812,127**		

Statistically significant mathematical models were estimated to simulate the number of cases per country, and an additional mathematical model that simulates the behavior of the pandemic in South America was also developed. All models obtained effectively explained the disease behavior since the R^2 was greater than 95 %, indicating that it can be measured over a maximum of 100 % (Table 2) (Martinez-Burgos *et al.*, 2019; 2021), reflecting low prognostic error.

Table 2. Mathematical models for each country and their characteristics.

Country	Cumulative cases model	R^2	Average forecast error	*p-value
Argentina	$e^{1.27+0.895\sqrt{days}}$	96.80	-12.040	0.00022
Bolivia	$e^{0.962\sqrt{days}}$	99.80	-12.080	0.00001
Brazil	4533,7*Days-243,9*$Days^2$ + 3,8*$Days^3$-0,01075*$Days^4$	99.96	-0.006	0.79000
Chile	$e^{2.306+\ln(\mathrm{days})}$	99.20	4751.000	0.00480
Ecuador	$\frac{1}{-0.00007571\ +\ 0.019045/\mathrm{days}}$	99.70	1349.000	0.04200
Colombia	$e^{2.75+0.706\sqrt{days}}$	99.80	141.000	0.00050
Paraguay	$e^{0.4736+0.699\sqrt{days}}$	98.00	-82.000	0.02800
Uruguay	$\sqrt{103046.5+77.36*\mathrm{days}^2}$	97.00	-10.000	0.04580
Perú	$e^{2.64+0.706*\ln(\mathrm{days})}$	99.90	-6682.000	0.03030
Venezuela	$e^{(2.54+0.0043*days^2)^2}$	99.40	8.630	0.01700
South America	$-307708\ +165.20*days^2$	98.20	0.054	0.74600

* Kolmogorov-Smirnov p-value of model residuals.

The mathematical models that simulated the behavior of the disease in Bolivia, Colombia, and Paraguay showed the same behavior of the mathematical model (Logarithm Y and sqrt of X: Y = exp (a + b * sqrt (X))). The same was observed for the mathematical models of Chile and Peru (Multiplicative: Y = X ^ b), whereas the models were completely different in other countries, including the general model for South America.

On the other hand, the Uruguay mathematical model and the general model for South America showed the lowest average errors and followed the behavior of a normal distribution. Therefore, when forecasting prognostic errors, they do not reach high values. Although the average error of the Venezuelan model had a lower average than the Uruguay model, the prognostic errors did not show a normal distribution behavior, which leads to the conclusion that the Uruguay behaved more similarly to reality, Although the models for several countries indicated that their residuals did not follow the pattern of a normal distribution, the average errors were significantly small compared to the average values of reported cumulative cases. For this reason, the models achieved R-squared values mostly above 96 %. Therefore, the regression models generated accurately describe the behavior of cumulative COVID-19 cases in the studied countries. In the case of the general model for South America, its low average absolute error followed a normal distribution. As seen in Figure 3, the mathematical model for Uruguay (Figure 3A) and the general model (Figure 3B) followed the behavior of positive cases reported for the disease.

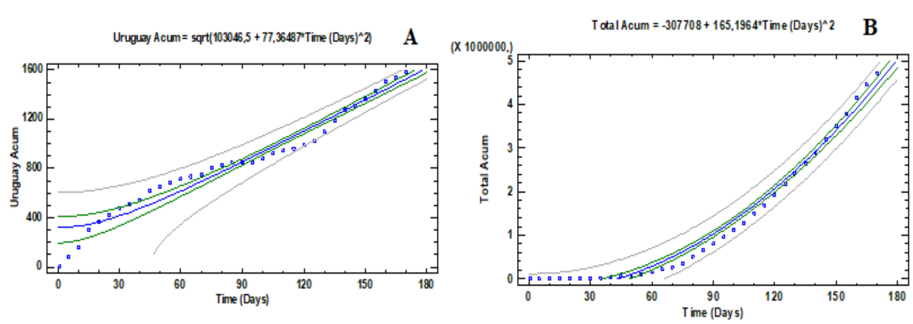


Figure 3. A) Adjusted model of disease behavior in Uruguay, B) Adjusted model of disease behavior in South America.

COVID-19 lockdown and global environment impact

Currently, conventional hydrocarbons are still one of the main energy sources in South America (IEA, 2020). However, fuel-burning is one of the practices that most negatively impact the environment, specifically compromising air quality (Xiu *et al*., 2018; Chu *et al*., 2020). Depending on the type of fuel burned, pollutant compounds such as particulate material are released into the atmosphere (PM_{10} and $PM_{2.5}$), in addition to greenhouse gases such as CO, CO_2, SO_2, and NO_2 (Salvador, 2018; Chu *et al*., 2020). According to the International Energy Agency (IEA, 2020), between 40 and 90 % of the energy consumed in South American countries comes from the burning of fossil fuels such as coal, natural gas, and oil. The exception is Paraguay, wherein only 25 % of the energy comes from these sources. This factor implies that many major cities in South America have problems associated with high concentrations of particulate matter (PM_{10} and $PM_{2.5}$) and greenhouse gases (COx, NOx, and SOx) (Romero-Lankao *et al*., 2013; Krzyzanowski *et al*., 2014), as seen in Figure 4 (Nedbor-Gross *et al*., 2018; Dantas *et al*., 2020; Debone *et al*., 2020; Pineda Rojas *et al*., 2020; Romero *et al*., 2020). During the health emergency caused by the SARS-CoV-2, one of the strategies to contain the spread of the disease in most South American countries was the application of strict quarantine measures, *e.g*., confinement and restriction of both people and automobile movement, which were the most effective measures applied in China (Chen *et al*., 2020; He *et al*., 2020), indirectly improving the quality of the air.

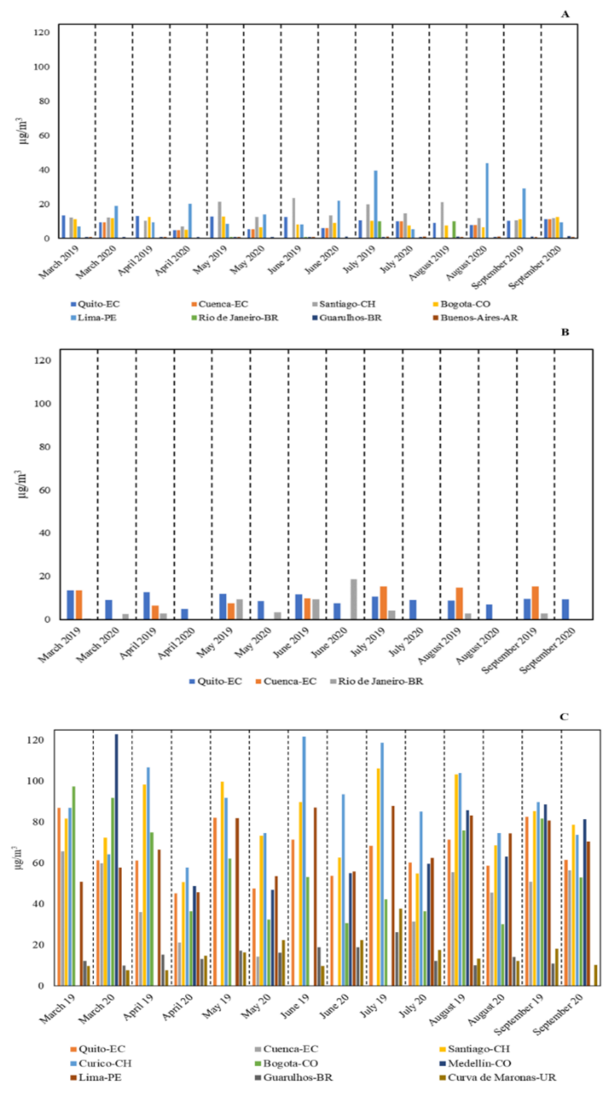
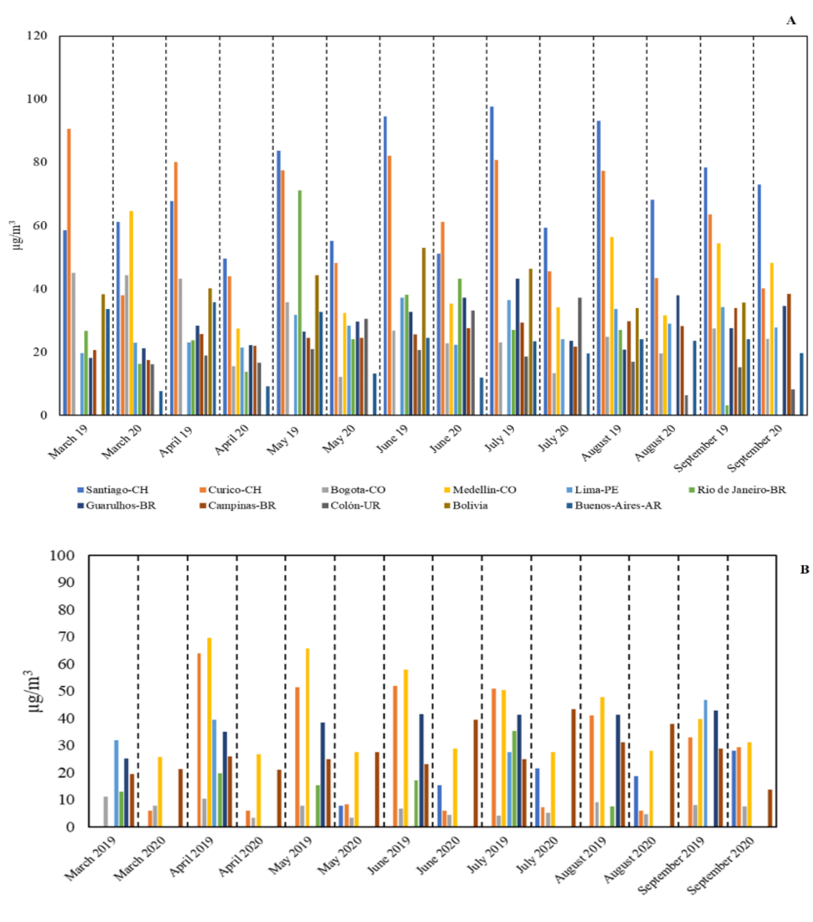


Figure 4. Concentrations of air pollutant emission in South American countries in 2019 and 2020. A) CO, B) SO_2; C) $PM_{2.5}$. EC: Ecuador, CH: Chile, AR: Argentina, PE: Peru, CO: Colombia, BR: Brazil, UR: Uruguai.

The data obtained on air quality during the quarantine periods in all studied South American cities revealed a significant reduction in at least one of the pollutants evaluated. In Lima, Peru, the CO concentrations decreased by up to 50 % between April and July 2020 compared to 2019. In Santiago, Chile, the air levels of CO decreased by approximately 30 % between April and September 2020. The same behavior was observed in Bogota, Colombia (Figure 4A). About SO_2, a slight decrease in the concentrations of this pollutant was observed in Quito, Ecuador (March 2019-September 2020) but the greatest reduction (approximately 60 %) was observed in May. In the city of Rio de Janeiro, Brazil, a decrease was only observed in May 2020 too compared to the same month of 2019. In other evaluated periods, the pollutant concentrations were higher in 2020 than those reported in 2019 (Figure 4B). In other countries, *e.g.*, Morocco, there was a significant reduction in the air SO_2 concentration during the lockdown period, from approximately 14 µg/m^3 before the lockdown to approximately 2 µg/m^3 during the lockdown (Otmani *et al.*, 2020). Northern China showed a similar situation, wherein the concentration of this pollutant in the environment decreased by approximately 30% during the mobility restriction period (Meng *et al.*, 2021). In the Yangtze River delta region, the air concentration of the same pollutant was reduced by 16 to 26 % (Li *et al.*, 2020).

Otherwise, lockdown periods also significantly reduced air contamination in terms of $PM_{2.5}$ (Figure 4C) and PM_{10} (Figure 5A). In Guarulhos, Brazil, the $PM_{2.5}$ levels were reduced by approximately 30 % in July 2020, whereas no reductions were observed in other months regarding the environmental concentration of $PM_{2.5}$. Quito, in Ecuador, is a city those experiences air quality problems, mainly with $PM_{2.5}$. In 2019, the $PM_{2.5}$ levels in that city were above 50 µg/m^3, classified as "very bad". However, the pollution levels in Quito were reduced by up to 50 % between April and July 2020, the period with mobility restrictions. For example, $PM_{2.5}$ reached concentrations between 25-50 µg/m^3 considered as "bad"; that is, less critical than the index recorded in 2019. Significant reductions in $PM_{2.5}$ pollution levels were also observed in Bogota, Colombia, whereas slight $PM_{2.5}$ reductions were observed in cities such as Cuenca, Curicó, Guarulhos, Lima, and Santiago de Chile. In China, some cities such as Shanghai, Hefei, Hangzhou, and Nanjing also showed significant $PM_{2.5}$ reductions of up to 50 %, decreasing from concentrations of 60 µg/m^3 before the lockdown to approximately 30 µg/m^3 during the lockdown (Li *et al.*, 2020).



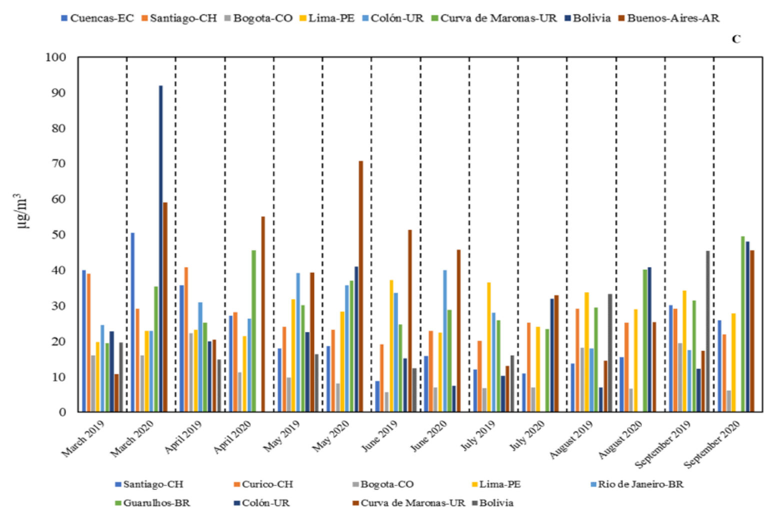


Figure 5. Concentrations of air pollutant emission in South American countries in 2019 and 2020. A) PM_{10}, B) NO_2 and C) O_3. EC: Ecuador, CH: Chile, AR: Argentina, PE: Peru, CO: Colombia, BR: Brazil, UR: Uruguai.

Some European countries, *e.g.*, Germany, Norway, Bosnia and Herzegovina, Sweden, Bulgaria, and Romania, also reported reductions in the environmental concentration of $PM_{2.5}$. However, the decreases were smaller than some reported in South America (Menut *et al.*, 2020).

About PM_{10}, the most significant reductions in pollution levels (of about 40 to 50 %) were observed in the cities of Curicó, Santiago de Chile, and Bogotá. In the latter, during April and May, the PM_{10} reduction was approximately 60 %. The case of the city of Bogotá stands out, where the average concentrations of PM_{10} decreased from 43 to 12 µg/m^3. In other words, it went from a "bad" cataloged index to a "very good" cataloged index. In other cities, *e.g.*, Rio Janeiro, Medellín, Guarulhos, and Lima, the reduction was around 20 % in 2019. In addition, significant decreases in atmospheric concentrations of NO_2 were also observed, mainly in the cities of Santiago de Chile and Lima, where the concentration decreased from the range of 50-60 to 7 and 25 µg/m^3, respectively (Figure 5B).

The air quality improvement in different South American cities and around the world can be mainly explained by the restrictions on mobility imposed by each country to contain the spread of COVID-19. For example, in Colombia, vehicular traffic was reduced by approximately 80 % (Statista, 2020). Consequently, the consumption of fuels, such as gasoline and diesel, decreased by 63 and 52 %, respectively. In addition, the electricity demand decreased by approximately 17 %, mainly due to several non-essential industries also stopping their operations. According to the Inter-American Development Bank (BID, 2020), vehicle traffic in cities such as Lima, Buenos Aires, São Paulo, and Santiago de Chile decreased by 90, 81, 81, and 72 %, respectively, in the first months of confinement (April and May). In addition, the demand for land and air transport also declined drastically. For example, in Colombia, Chile, Uruguay, Brazil, Peru, and Ecuador the land transport demand decreased by 80, 75, 75, 65, 56, and 50 %, respectively (García *et al.*, 2020). Furthermore, significant reductions in electricity consumption were also observed during the lockdown period in South America. According to the Ministry of Mines and Energy of Peru, the reduction in energy consumption during the social isolation period was approximately 48 GWh each day, approximately 36 % of the total energy consumed in that country. Thermal energy generation also went from 25 to just 5 %, directly impacting air quality. In Bolivia, Argentina, and Brazil, the reduction in energy demand amounted to 29 % (~ 9 GWh), 26 % (~ 5300 MWh), and 22 % (~ 15,000 MWh), respectively. On the other hand, Chile was one of the countries that least reduced energy consumption, with an approximate decrease of only 6 % (García *et al.*, 2020).

Another environmental parameter evaluated was the concentration of O_3 in the environment (Figure 5C). Ground-level ozone is associated with respiratory problems, especially in children, elders and lung-diseased people, even causing death (Andrade *et al.*, 2017). In the cities of Rio de Janeiro, Guarulhos, and Montevideo, the environmental concentration of O_3 increased. The same behavior was observed in other countries during the lockdown period. For example, Sharma *et al.* (2020) reported a 1 % increase in the air concentration of O_3 in India. Tobías *et al.* (2020) also reported an increase of approximately 57 % in the O_3 concentration, from 42 μg/m^3 before the lockdown to 66 μg/m^3 during the lockdown in Barcelona. According to Nakada and Urban (2020), Andrade *et al.* (2017), and Tobías (2020), the increase in the O_3 concentration is associated with the reduction of NO_x in environments with low volatile organic compounds, as the precursors of O_3 are more available to be turned into ozone and not attached to NO_x. In other cities, such as Lima and Santafé de Bogota, the concentration of O_3 slightly decreased from April to September 2020. In Santiago de Chile and Curicó, the concentration of ozone in the environment also decreased, which could be associated with pollutant dispersion (Nakada and Urban 2020).

Conclusions

Given the analysis of the behavior and spread of the COVID-19 pandemic in South America, as well as the improvement in air behavior during quarantine, it is reinforced that this region had a rapid spread of the virus and a distinct profile now of the pandemic. Some countries responded quickly to the emergency, implementing lockdown and quarantine measures quickly, as observed in Uruguay, resulting in greater precision and fewer errors in mathematical models. This country demonstrated the ability to adjust more easily to the needs imposed by the crisis, resulting in more accurate projections about the spread of the virus.

Air quality showed notable changes during the quarantine period. Significant reductions in pollution were evident, mainly from atmospheric substances NO2 and PMs, as well as a decrease in energy consumption and reduced mobility of vehicles, people and industrial activities. In the pandemic scenario, the direct relationship between mobility restrictions and improvements in air quality became evident, as well as the importance of science and technology. Therefore, these reinforce the need to implement sustainable policy results in large cities in South American countries that consider the intrinsic relationship between human activity and environmental preservation, in order to maintain good air quality, as well as predicting propagation behavior in order to provide information for future health measures in cases of other diseases.

Acknowledgments

This work was funded by grants from the Coordination for the Improvement of Higher Education Personnel (CAPES), a Brazilian research funding agency (Project No. 88881.505280/2020-01).

References

Andrade, M., Kumar, P., Dias, E., Freitas, D., Yuri, R., Martins, J., Martins, L.D., Nogueira, T., Perez-Martinez, P., Maura, R., Miranda, D., Albuquerque, T., Luiz, F., Gonçalves, T., Oyama, B., Zhang, Y. (2017). Air quality in the megacity of São Paulo: Evolution over the last 30 years and future perspectives. *Atmospheric Environment*, 159, 66-82.

Bell, M. L., Davis, D. L., Gouveia, N., Borja-Aburto, V. H., Cifuentes, L. A. (2006). The avoidable health effects of air pollution in three Latin American cities: Santiago, São Paulo, and Mexico City. *Environmental Research*, 100(3), 431-440.

BID. (2020). *Traffic congestion intensity by country. Banco Interamericano de Desarrollo (BID)* [on line] available from: https://code.iadb.org/en/tools/coronarivus-impact-toolbox [accessed 9 January 2021].

Chen, K., Wang, M., Huang, C., Kinney, P. L., Anastas, P. T. (2020). Comment air pollution reduction and mortality benefit during the COVID-19 outbreak in China. *Comment*, 4, e210-e212.

Chu, H., Xiang, L., Nie, X., Ya, Y., Gu, M., Jiaqiang, E. (2020). Laminar burning velocity and pollutant emissions of the gasoline components and its surrogate fuels: A review. Fuel, 269 (February), 117451.

Collivignarelli, M. C., Abbà, A., Bertanza, G., Pedrazzani, R., Ricciardi, P., Carnevale Miino, M. (2020). Lockdown for CoViD-2019 in Milan: What are the effects on air quality? *The Science of the Total Environment*, 732, 139280.

Dantas, G., Siciliano, B., França, B. B., da Silva, C. 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.

Debone, D., Leirião, L. F. L., Miraglia, S. G. E. K. (2020). Air quality and health impact assessment of a truckers' strike in Sao Paulo state, Brazil: A case study. *Urban Climate*, 34, 100687.

Faiz, A., Gautam, S., Burki, E. (1995). Air pollution from motor vehicles: issues and options for Latin American countries. *Science of the Total Environment*, 169 (1-3), 303-310.

He, G., Pan, Y., Tanaka, T. (2020). The short-term impacts of COVID-19 lockdown on urban air pollution in China. *Nature Sustainability*, 3, 1005-1011.

IEA. (2020). *Analysis shapes policies to enable the world to meet climate, energy access and air quality goals while maintaining a strong focus on the reliability and affordability of energy for all. International Energy Agency (IEA)* [on line] avalilable from: https://www.iea.org/news/world-energy-outlook-2019-highlights-deep-disparities-in-the-global-energy-system [accessed 9 January 2021].

Krzyzanowski, M., Apte, J. S., Bonjour, S. P., Brauer, M., Cohen, A. J., Prüss-Ustun, A. M. (2014). Air pollution in the mega-cities. *Current Environment Health Report*, 10, 185-191.

García, F., Moreno, A., Schuschny, A. (2020). *Análisis de los impactos de la pandemia del COVID-19 sobre el sector energético de América Latina y el Caribe*. Quito: Organización Latinoamericana de Energía (Olade).

Li, L., Li, Q., Huang, L., Wang, Q., Zhu, A., Xu, J., Liu, Z., Li, H., Shi, L., Li, R., Azari, M., Wang, Y., Zhang, X., Liu, Z., Zhu, Y., Zhang, K., Xue, S., Ooi, M. C. G., Zhang, D., Chan, A. (2020). Air quality changes during the COVID-19 lockdown over the Yangtze River Delta Region: An insight into the impact of human activity pattern changes on air pollution variation. *Science of the Total Environment*, 732, 139282.

Martinez-Burgos, W. J., Sydney, E. B., Brar, S. K., Tanobe, V. O. de A., Pedroni Medeiros, A. B., Cesar de Carvalho, J., Soccol, C. R. (2019). The effect of hydrolysis and sterilization in biohydrogen production from cassava processing wastewater medium using anaerobic bacterial consortia. *International Journal of Hydrogen Energy*, 44(47), 25551-25564.

Martinez-Burgos, W. J., Sydney, E. B., de Paula, D. R., Medeiros, A. B. P., De Carvalho, J. C., Molina, D., Soccol, C. R. (2021). Hydrogen production by dark fermentation using a new low-cost culture medium composed of corn steep liquor and cassava processing water: Process optimization and scale-up. *Bioresource Technology*, 320(Part B), 124370.

Meng, J., Li, Z., Zhou, R., Chen, M., Li, Y., Yi, Y., Ding, Z., Li, H., Yan, L., Hou, Z., Wang, G. (2021). Enhanced photochemical formation of secondary organic aerosols during the COVID-19 lockdown in Northern China. *Science of the Total Environment*, 758, 143709.

Menut, L., Bessagnet, B., Siour, G., Mailler, S., Pennel, R., Cholakian, A. (2020). Impact of lockdown measures to combat Covid-19 on air quality over Western Europe. Science of the Total Environment, 741, 140426.

Nakada, L. Y. K., Urban, R. C. (2020). COVID-19 pandemic: Impacts on the air quality during the partial lockdown in São Paulo state, Brazil. *Science of the Total Environment*, 730, 139087.

National Library of Medicine. (2021). *SARS-CoV-2 Data Hub* [on line] available from: https://www.ncbi.nlm.nih.gov/labs/virus/vssi/#/ [accessed 9 January 2021].

Nedbor-Gross, R., Henderson, B. H., Pérez-Peña, M. P., Pachón, J. E. (2018). Air quality modeling in Bogota Colombia using local emissions and natural mitigation factor adjustment for re-suspended particulate matter. *Atmospheric Pollution Research*, 9(1), 95-104.

Otmani, A., Benchrif, A., Tahri, M., Bounakhla, M., Chakir, E. M., El Bouch, M., Krombi, M. (2020). Impact of Covid-19 lockdown on PM10, SO2 and NO2 concentrations in Salé City (Morocco). *Science of the Total Environment*, 735(2), 139541.

Paital, B., Agrawal, P. K. (2021). Air pollution by NO2 and PM2.5 explains COVID-19 infection severity by overexpression of angiotensin-converting enzyme 2 in respiratory cells: a review. *Environmental Chemistry Letters*, 19(1), 25-42.

Pan American Health Organization, World Health Organization. (2020). *Epidemiological alert novel coronavirus (nCoV)* [on line] available from: https://www.paho.org/en/documents/epidemiological-alert-novel-coronavirus-ncov-16-january-2020 [accessed 9 January 2021].

Pericàs, J. M., Hernandez-Meneses, M., Sheahan, T. P., Quintana, E., Ambrosioni, J., Sandoval, E., Falces, C., Marcos, M. A., Tuset, M., Vilella, A., Moreno, A., Miro, J. M., (2020). COVID-19: From epidemiology to treatment. *European Heart Journal*, 41(22), 2092-2108.

Pineda Rojas, A. L., Borge, R., Mazzeo, N. A., Saurral, R. I., Matarazzo, B. N., Cordero, J. M., Kropff, E. (2020). High PM10 concentrations in the city of Buenos Aires and their relationship with meteorological conditions. *Atmospheric Environment*, 241, 117773.

Rahman, H. S., Sleman, M., Hassan, R., Hassan, H. (2020). The transmission modes and sources of COVID-19: A systematic review. *International Journal of Surgery Open*, 26, 125-136.

Romero, Y., Chicchon, N., Duarte, F., Noel, J., Ratti, C., Nyhan, M. (2020). Quantifying and spatial disaggregation of air pollution emissions from ground transportation in a developing country context: Case study for the Lima Metropolitan Area in Peru. *Science of the Total Environment*, 698, 134313.

Romero-Lankao, P., Qin, H., Borbor-Cordova, M. (2013). Exploration of health risks related to air pollution and temperature in three Latin American cities. *Social Science & Medicine*, 83, 110-118.

Salvador, P. (2018). Ozone, SOx and NOx, particulate matter, and urban air. In: *Encyclopedia of the Anthropocene*. Madrid: Elsevier Inc.

Sharma, S., Zhang, M., Anshika, Gao, J., Zhang, H., Kota, S. H. (2020). Effect of restricted emissions during COVID-19 on air quality in India. *Science of the Total Environment*, 728, 138878.

Statista. (2020). *Coronavirus traffic congestion impact in Latin America with Waze data* [on line] available from: https://www.statista.com/statistics/1116745/traffic-congestion-latin-america-cities-change-covid-19-impact/ [accessed 9 January 2021].

Vedova-Costa, J. M. Dela, Ramos, E. L. P., Boschero, R. A., Ferreira, G. N., Soccol, V. T., Santiani, M. H., Pacce, V. D., Lustosa, B. P. R., Vicente, V. A., Soccol, C. R. (2021). A review on COVID-19 diagnosis tests approved for use in Brazil and the impact on pandemic control. *Brazilian Archives of Biology and Technology*, 64, 1-14.

Wang, L., Wang, Y., Ye, D., Liu, Q. (2020). Review of the 2019 novel coronavirus (SARS-CoV-2) based on current evidence. *International Journal of Antimicrobial Agents*, 55(6), 105948.

World Health Organization. (2021a). *Coronavirus disease (COVID-19) dashboard. WHO Coronavirus (COVID-19)* [on line] available from: https://covid19.who.int/ [accessed 29 August 2021].

World Health Organization. (2021b). *Air pollution* [on line] available from: https://www.who.int/data/gho/data/themes/theme-details/GHO/air-pollution [accessed 19 March 2021].

Wu, F., Zhao, S., Yu, B., Chen, Y. M., Wang, W., Song, Z. G., Hu, Y., Tao, Z. W., Tian, J. H., Pei, Y. Y., Yuan, M. L., Zhang, Y. L., Dai, F. H., Liu, Y., Wang, Q. M., Zheng, J. J., Xu, L., Holmes, E. C., Zhang, Y. Z. (2020). A new coronavirus associated with human respiratory disease in China. *Nature*, 579(7798), 265-269.

Xiu, M., Stevanovic, S., Rahman, M. M., Pourkhesalian, A. M., Morawska, L., Thai, P. K. (2018). Emissions of particulate matter, carbon monoxide and nitrogen oxides from the residential burning of waste paper briquettes and other fuels. *Environmental Research*, 167, 536-543.

Zaconeta, A., Heinen, B. G., Salles, Y. V. M., Matsunaga, M. E. da C. (2020). SARS-CoV-2: What prevents this highly contagious virus from reaching the fetus? *Placenta*, 104, 303.

Zhou, P., Yang, X., Lou, C., Wang, X. G., Hu, B., Zhang, L., Zhang, W., Si, H. R., Zhu, Y., Li, B., Huang, C. L., Chen, H. D., Chen, J., Luo, Y., Guo, H., Jiang, R., Liu, M. Q., Chen, Y., Shen, X. R., Wang, X., Zheng, X. S., Zhao, K., Chen, Q. J., Deng, F., Liu, L. L., Yan, B., Zhan, F. X., Wang, Y. Y., Xiao, G. F., Shi, Z. L. (2020a). A pneumonia outbreak associated with a new coronavirus of probable bat origin. *Nature*, 579(7798), 270-273.

Zhou, F., Yu, T., Du, R., Fan, G., Liu, Y., Liu, Z., Xiang, J., Wang, Y., Song, B., Gu, X., Guan, L., Wei, Y., Li, H., Wu, X., Xu, J., Tu, S., Zhang, Y., Chen, H., Cao, B. (2020b). Clinical course and risk factors for mortality of adult inpatients with COVID-19 in Wuhan, China: a retrospective cohort study. *The Lancet*, 395(10229), 1054-1062.

Zhu, Y., Xie, J., Huang, F., Cao, L. (2020). The mediating effect of air quality on the association between human mobility and COVID-19 infection in China. *Environmental Research*, 189, 109911.

Editor Asociado: *Gustavo Adolfo Morillo Díaz*
Centro de Investigación del Agua, Facultad de Ingeniería
Universidad del Zulia, Maracaibo, 4001, Venezuela.
gmorillo@fing.luz.edu.ve

UNIVERSIDAD DEL ZULIA

REVISTA TECNICA

DE LA FACULTAD DE INGENIERIA
UNIVERSIDAD DEL ZULIA

Volumen 46. Año 2023, Edición continua

*Esta revista fue editada en formato digital y publicada en diciembre 2023, por el **Fondo Editorial Serbiluz, Universidad del Zulia. Maracaibo-Venezuela***

www.luz.edu.ve
www.serbi.luz.edu.ve
www.produccioncientificaluz.org