Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Increased tropospheric ozone levels as a public health issue during COVID-19 lockdown and estimation the related pulmonary diseases

Khatereh Anbari a, Yusef Omidi Khaniabadi b, Pierre Sicard c, Hasan Raja Naqvi d, Rajab Rashidi a, * a Social Determinants of Health Research Center, School of Medicine, Lorestan University of Medical Sciences, Khorramabad, Iran
b Occupational and Environmental Health Research Center, Petroleum Industry Health Organisation (PIHO), Ahvaz, Iran
c ARGANS, 260 Route Du Pin Montard, 06410, Biot, France
d Department of Geography, Faculty of Natural Sciences, Jamia Millia Islamia, New Delhi, India

* Corresponding author.
E-mail addresses: rajab_rashidi@yahoo.com, rashidi.r270@gmail.com (R. Rashidi).

https://doi.org/10.1016/j.apr.2022.101600
Received 22 July 2022; Received in revised form 15 November 2022; Accepted 15 November 2022
Available online 21 November 2022
1309-1042/© 2022 Turkish National Committee for Air Pollution Research and Control. Production and hosting by Elsevier B.V. All rights reserved.

ARTICLE INFO

Keywords:
Air pollution
COVID-19
Health effect
O₃
Mortality

ABSTRACT

The aims of this study were to i) investigate the variation of tropospheric ozone (O₃) levels during the COVID-19 lockdown; ii) determine the relationships between O₃ concentrations with the number of COVID-19 cases; and iii) estimate the O₃-related health effects in Southwestern Iran (Khorramabad) over the time period 2019–2021. The hourly O₃ data were collected from ground monitoring stations, as well as retrieved from Sentinel-5 satellite data for showing the changes in O₃ levels pre, during, and after lockdown period. The concentration-response function model was applied using relative risk (RR) values and baseline incidence (BI) to assess the O₃-related health effects. Compared to 2019, the annual O₃ mean concentrations increased by 12.2% in 2020 and declined by 3.9% in 2021. The spatiotemporal changes showed a significant O₃ increase during COVID-19 lockdown, and a negative correlation between O₃ levels and the number of COVID-19 cases was found (r = -0.59, p < 0.05). In 2020, the number of hospital admissions for cardiovascular diseases increased by 4.0 per 10⁵ cases, the mortality for respiratory diseases increased by 0.7 per 10⁵ cases, and the long-term mortality for respiratory diseases increased by 0.9 per 10⁵ cases. Policy decisions are now required to reduce the surface O₃ concentrations and O₃-related health effects in Iran.

1. Introduction

Air pollution in recent years became one of the major environmental and public health issues, with the industrialization, urbanization, and growing population (Amoatey et al., 2021; Anbari et al., 2022; Boogaard et al., 2019; Landrigan et al., 2018). Acute and chronic exposure to air pollutants has harmful effects on human health (Burnett et al., 2014; Khaniabadi et al., 2019a). Tropospheric ozone (O₃) is formed by photochemistry from nitrogen oxides (NOₓ), volatile organic compounds (VOCs), and methane (De Marco et al., 2022; Heroux et al., 2015; Naghian et al., 2022). Over the last years, the urbanization and fossil fuel consumption led to rising background O₃ levels worldwide (Li et al., 2020a).

In cities worldwide, rising O₃ levels (Sicard, 2021) is associated with hospital admissions for cardiovascular and respiratory diseases, and mortality (Li et al., 2020b; Organization, 2021). To date, surface O₃ is a serious environmental problem in Europe, the United States, and across Asia, and is one of the most harmful air pollutants affecting human health, vegetation, materials, and biodiversity (Agathokleous et al., 2020; Carbajal-Arroyo et al., 2011; Sicard et al., 2019; Zhu et al., 2022).

The short-term O₃ effects on the respiratory systems is well-established, especially in sensitive people infected by obstructive chronic pulmonary diseases (Faustini et al., 2019). For the human health protection, the World Health Organization (WHO) set a limit value of 50 ppb calculated as daily 8-h running mean average. Previous studies e.g., in Beijing (Li et al., 2019), Isfahan (Abdolahnejad et al., 2018), Nice and Rome (Sicard et al., 2019), Suwon (Jeong, 2013), Hainan (Li et al., 2020a), Catalonia (Rovira et al., 2020), Shiraz (Bonyadi et al., 2020), Cape Town (Adebayo-Ojo et al., 2022), Kuwait (Al-Hemoud et al., 2021), and Paris (Filleul et al., 2006) have reported an increased rate of...
mortality and morbidity for exposure to the O\textsubscript{3}. The chronic exposure to the O\textsubscript{3} levels led to 147,100 deaths within 13,000 cities in the world in 2019 (Malashock et al., 2022). The number of premature deaths due to O\textsubscript{3} exposure increased by 0.55 deaths per 10\textsuperscript{6} people in the Europe Union in 2000–2017 (Stafoggia et al., 2022).

To assess the health effects due to O\textsubscript{3} exposure, few studies used the concentration-response functional model by using the relative risk, and baseline incidence values. This method was used in Ahvaz for estimating related respiratory diseases mortality by O\textsubscript{3} exposure in the period 2012–2018 (Naghan et al., 2022). Similar O\textsubscript{3} risk assessments were conducted based on concentration-response (C-R) function model in Texas (Zu et al., 2017), Surat City (Jariwala and Kapadia, 2022), Tabriz (Barzeghar et al., 2019), Canada (Zhao et al., 2021), Ahvaz (Amoatey et al., 2019), Mexico city and New York (Gurjar et al., 2010), Tehran (Hadei et al., 2017a), and Catalonia (Rovira et al., 2020).

During COVID-19 lockdown in 2020, reduced vehicle traffic and anthropogenic activities led to reduced emissions of NO\textsubscript{x} and fine particles in cities, while the O\textsubscript{3} levels significantly increased e.g., in Suzhou (Wang et al., 2021a), Rome and Nice (Sicard et al., 2020), São Paulo (Nakada and Urban, 2020), Baghdad (Hashim et al., 2021), Barcelona and Madrid (Querol et al., 2021), Vienna (Brancher, 2021), Las Vegas and Los Angeles (Chen et al., 2020), San Fernando (Morales-Solís et al., 2021), and London (Vega et al., 2021). In China, a conducted study in 31 provincial cities illustrates a decline in NO\textsubscript{2} related to reducing of traffic emissions due to social distances for COVID-19 lockdown resulted in rising O\textsubscript{3} levels in 2020 (Nie et al., 2021).

In our study, we have investigated the spatial variation of surface O\textsubscript{3} levels during the COVID-19 lockdown; ii) determined the relationships between O\textsubscript{3} concentrations with the number of COVID-19 cases; and iii) estimated the O\textsubscript{3}-related health effects in Southwestern Iran (Khorramabad) over the time period 2019–2021.

2. Materials and methods

2.1. The study area

Khorramabad (Fig. 1), with a semi-humid Mediterranean city is located in the southwest region of Iran (33°48’N; 48°35’E, 1147 m a.s.l.). This city with a population over 540,000 inhabitants, is the capital city of Lorestan Province. Due to the climate properties, the annual means of air temperature and precipitation are respectively 17.2 °C and 512 mm. Desert dust from neighbor countries in the Middle Eastern area is the main source of ambient pollution (Daryanoosh et al., 2018). Moreover, the petrochemical industries, heavy road traffic, and VOCs emissions have intensified poorly air quality in this area (Omidi Khaniabadi et al., 2019).
2.2. The $O_3$ concentrations and COVID-19 data collection

This study was performed using hourly $O_3$ data from two ground monitoring stations managed by the Environmental Protection Agency located in Khorramabad. The hourly data were collected from January 1, 2019 to December 31, 2021. The daily maximum 8-h moving average levels were obtained from at least 75% of valid hourly data per day. The number of COVID-19 cases was provided by the six public and private hospitals in Khorramabad, from March 21, 2020 to March 20, 2021 to assess the relationships with $O_3$ concentration.

2.3. Spatial variation

Sentinel-5 satellite images were used to analyze the spatial distribution of $O_3$ concentrations over Iran at 3.5 $\times$ 7.0 km of spatial resolution by using Google Earth Engine for geospatial analysis, and for three time periods: before (21st February to March 21, 2020), during (22nd March to April 21, 2020), and post-COVID-19 lockdown (22nd April to May 21, 2020).

2.4. Estimation of human health exposure

To estimate the population exposure to $O_3$ levels, at first standard Z-scores were identified in time series. The concentration-response (C-R) is a developed model from different meta-analyses and systematic reviews of health effects due to exposure to different air pollutants in the world (Amoatey et al., 2020; Jariwala and Kapadia, 2022; Naghan et al., 2022). For that, we need three parameters including the number of people at-risk (N) in a city, the baseline incidence (BI), and the relative risk (RR) values.

The RR value is the probability to develop a disease in a group in relation to the contact with a certain air pollutant, per each 5 ppb increase in concentration (Eq. (1)), and obtained from published epidemiological studies. The risk ratio taken from epidemiological studies in local or national scales are more robust for risk assessment (Khanibadi and Sicard, 2021); nevertheless use of obtained RR from the different conducted studies in the other regions such as United States and Europe is acceptable by the WHO to investigate the risk of air pollution where epidemiological studies are missing. We used the RR values recommended by the WHO (Table 1) and published by Héroux et al. (2015),

$$ RR = \exp(\beta \times (X - X_0)) $$

where $\beta$ regulates the RR value increasing, also parameter $X$ is the amount of air pollutant and $X_0$ is background level where there is not observed health effect (De Marco et al., 2018). The city-specific baseline incidence (BI per 10$^5$ inhabitants) was used for each health endpoint. The BI was provided by the six public and private hospitals in Khorramabad. Furthermore, the attributable proportion (AP%) among a population at risk, $P_{(i)}$, is a fraction of health effect statistically associated with exposure to a certain population in a given time period (Eq. (2)).

$$ AP = \sum \left( \frac{[RR(c) - 1] \times P(c)}{\sum [RR(c) \times P(c)]} \right) $$

where AP and RR(c) are respectively attributable proportion and relative risk for a certain health effect in category “c” acquired from the exposure-response functions resulting from published meta-analysis and epidemiological studies (Hadi et al., 2017b; Moradi et al., 2022; Rovira et al., 2020), and P(c) defined as the proportion of exposed population in category “c” exposure (Fattore et al., 2011; Gurjar et al., 2010; Khanibadi et al., 2017b).

In an at-risk population the number of cases, NC, per 10$^5$ people, correlated with a specific health effect because of exposure to air pollutant can be estimated by $NC = BI \times AP$, as well as NE, refers to the number of excess cases among people attributed to air pollutant in category “c” exposure, can be estimated by $NE = 10^{-3} \times [NC_c \times N]$, where N is the number of at-risk population contacted with a certain air pollutant (Ambari et al., 2022; De Marco et al., 2018).

The indicator of Sum of Ozone Means Over 35 ppb (SOMO35), is recommended by the WHO to assess of the $O_3$-related health effect. The SOMO35 (in ppb days) is identified as the annually sum of maximum daily 8-h moving means of $O_3$ higher than 35 ppb (Eq. (3)).

$$ SOMO35 = \sum_{t=1}^{\text{max}} \{0.1(C_t - 70)\} $$

where $C_t$ and $i$ respectively refers to the maximum daily $O_3$ mean levels (in ppb) and the number of days over year (365 or 366). Since SOMO35 is sensitive to missing data, it is actually modified to full annual coverage by valid $O_3$ daily concentrations ($N_{valid}$) corresponding to following formula (Eq. (4)).

$$ SOMO35 = SOMO35_{uncorrected} \times \frac{N_{valid}}{N_{valid}} $$

For the health effects due to $O_3$ exposure, the model evaluates the integrated exposure-response (IER) function (Eq. (6)).

$$ RR = \exp(\beta \cdot SOMO35_{uncorrected} / N_{valid}) $$

where $\beta$, $C_{max}$ (in ppb), and $X_0$ are respectively the increase in the amount of RR, the maximum daily 8-h average $O_3$ concentrations, and the $O_3$ daily concentration.

The rate of incidence the specified health outcome at a population level (BI, per 100,000) can be used for SOMO35 above a defined reference level by Eq. (7).

$$ E = BI \times PAF $$

where BI is an obtained value of certain health effect in a population, PAF is the population attributable fraction which calculated by the amount of RR and multiplying the population (P) by following Eq. (8): $PAF = RR - 1 / RR$.

The WHO recommended that to estimate the mortality and morbidity between people more than 30-year-old and at-risk population related to $O_3$ exposure, it can be used the C-R function model (Burnett et al., 2014; Faridi et al., 2018; Héroux et al., 2015).

In this study, the rate of hospital admissions due to cardiovascular diseases (HA-CVD), respiratory diseases mortality (MRD) for people over 30-year-old, and long-term respiratory diseases mortality (LTMRD) were assessed by using $O_3$ concentrations between 2019 and 2021. Based on ICD-10, the codes J00-J98 are related to respiratory disease, J95 and J96 is related to respiratory mortality, I00–I99 are

| Health outcomes                  | BI$^a$ | RR$^b$ per 5 ppb (95% CI) | Ref.                             |
|----------------------------------|-------|---------------------------|---------------------------------|
| Hospital admission-CVD           | 436   | 1.009 (1.005–1.0127)      | (De Marco et al., 2022), (Héroux et al., 2015) |
| Respiratory mortality (age ≥50) | 44–53 | 1.014 (1.005–1.024)       | (De Marco et al., 2022), (Héroux et al., 2015) |
| Long-term respiratory mortality  | 66    | 1.013 (1.005–1.024)       | Jariwala and Kapadia (2022)     |

$^a$ Baseline incidence.
$^b$ Relative risk.
$^c$ Confidence interval.
associated to cardiovascular disease.

Table 1 illustrates the amounts of BI and RR to assess the health effects attributed to O$_3$ exposure in Khorramabad (Iran). Normal distribution of data was analyzed by nonparametric test of the Kolmogorov-Smirnov 1-sample D-test. The analyses of correlations between the O$_3$ concentrations and the number of COVID-19 cases were performed by linear regression and Pearson correlation.

3. Results and discussion

3.1. Surface O$_3$ concentrations and COVID-19 cases

The city-averaged annual O$_3$ concentrations from 2019 to 2021 were assessed (Fig. 2). The highest annual mean concentration was observed in 2020 during COVID-19 (15.8 ppb). The O$_3$ concentrations in 2020 increased by 12.2% compared to 2019 and declined by 3.9% in 2021. High levels of sand from the Middle Eastern desert (Broomandi et al., 2022) reached Southwestern Iran leading to high level of PM (Khanibadi et al., 2017a, 2019b; Omidi Khanibadi et al., 2019; Rashidi et al., 2022). The high PM levels led to lower solar radiation, and by consequence to lower O$_3$ formation (Anbari et al., 2022; Grange et al., 2021; Higham et al., 2021; Siciliano et al., 2020), but also to destruction of O$_3$ on PM surface (Sicard et al., 2020). In Hanoi, with 20% increase in the surface solar activity radiation due to lower PM$_{2.5}$ concentrations, 41% increase was observed in the O$_3$ levels during COVID-19 lockdown (Nguyen et al., 2022).

Our results showed that more than 8560 COVID-19 cases were admitted to hospitals in Khorramabad from March 21, 2020 to March 20, 2021. In 2020, the number of COVID-19 cases was significantly and negatively correlated ($r = -0.59$, $p < 0.05$) to surface O$_3$ levels (Fig. 2).

A similar negative association was observed between COVID-19 cases and O$_3$ concentration in 2020 in Baghdad (Iraq) (Hashim et al., 2021). The dramatically reducing in the human activities and social distances may be the reasons for decline in COVID-19 cases and the increase in O$_3$ levels in the cities (Chen et al., 2020). The O$_3$ concentrations in Milan increased in 2020, but they reported that there was a positive correlation among COVID-19 cases and O$_3$ levels (Zoran et al., 2020), which do not confirm by our paper.

3.2. Spatial variation in Iran during COVID-19 lockdown

The spatiotemporal changes of surface O$_3$ levels in Iran showed that there is an increase during COVID-19 lockdown, ranging from 0.1355 to 0.1444 mol $\text{O}_3\text{ m}^{-3}$ (i.e., 32.58-34.73 ppb). Investigation for three-months pre- (21st February to 21st March) and post-lockdown (22nd March to 21st April) periods showed an increase of surface O$_3$ levels by 53.7% during lockdown compared to the previous month, and a reduction of 6.0% after lockdown. During lockdown, the highest change of O$_3$ levels was observed in the north-western Iranian provinces (Ardabil, West- and East-Azerbaijan, Urmia, and Zanjan), and the lowest change was observed in the southeastern areas (Sistan and Baluchistan province). The mechanism of related factors for high concentrations of O$_3$ not well studied but frequently increased during recent years with decreasing in the PM concentrations (Chen et al., 2021). The O$_3$ levels increased in March–April in Iran (Naqvi et al., 2021), then decreased in last days April 2020. In Tehran (Iran), the O$_3$ levels increased by 53.7% in 2020 compared to averaged 5-years ago at Aghdasieh station (Aghashariatmadari, 2021), and by 28.8% at Sharif-University station compared to the same period in 2019 (Broomandi et al., 2020). In Ardabil the monthly changes during lockdown increased O$_3$ levels by 51% compared to two months before COVID-19 lockdown (Rad et al., 2021).

In Khorramabad, the O$_3$ mean concentrations increased from 11.5 to 15.4 ppb during the lockdown. The results also indicated that O$_3$ mean concentrations increased during the lockdown (22nd March to April 21, 2020) by 33.8% in Khorramabad (Fig. 4). The annual O$_3$ mean concentrations increased by 12.2% between 2019 and 2020. This increase was also observed in Europe, the United States, and across Asia at the COVID-19 lockdown (Brix-Redon et al., 2021; Lian et al., 2020; Tobías et al., 2020). In six cities in the Europe and China, the O$_3$ concentration was increased during the lockdown (Sicard et al., 2020) which confirms our results.

Similar observations were reported in the conducted studies in Rio de Janeiro (Siciliano et al., 2020), Hanoi (Nguyen et al., 2022), Baghdad (Hashim et al., 2021), Tel-Aviv (Agami and Dayan, 2021), Barcelona (Tobías et al., 2021), Almaty (Kerimray et al., 2020), and Jiangsu (Bhatti et al., 2021). When the lockdown period started, the number of emission sources, volume of road traffic, and the air pollutants (PM$_{2.5}$ and NO$_x$) concentrations were dropped (Wang et al., 2021b); dropping in NO$_x$ and VOC-limited background, resulted in higher O$_3$ levels (Tobías et al., 2020).

3.3. Human health effect

The number of hospital admissions for cardiovascular diseases (6.6, 10.6, and 8.3 per $10^5$ cases), premature deaths for respiratory diseases (4.7, 5.4, and 4.9 per $10^5$ cases), and long-term premature deaths for respiratory diseases (1.7, 2.6, and 2.2 per $10^5$ cases) due to O$_3$ exposure above 5 ppb were obtained in 2019, 2020, and 2021, respectively (Table S1). HA-CVD, MRD, and LT-MRD increased by 60.6%, 14.8%, and 52.9% per $10^5$ cases in 2020 due to higher O$_3$ exposure (Schwarz et al., 2021) and then decreased by 21.0%, 8.9%, and 15.4% per $10^5$ cases in 2021 when annual mean of O$_3$ levels was reduced. In China, the authors observed a positive relationship between increase in O$_3$ levels and the risk of premature mortality, especial between exposure to O$_3$ and the risk of respiratory diseases and mortality (Liu et al., 2017). A study illustrated that the early O$_3$ exposure resulted in changes in the
conducting airways, and by increase in age, the potential relative risk increased due to O$_3$-related health effect (Vinikoor-Imler et al., 2014). The number of HA-CVD and MRD in 2020 and 2021, without COVID-19 effect, for O$_3$ exposure were HA-CVD = 6.1 and 4.9 per 10$^5$ cases at-risk population, MRD = 4.0 and 3.6 per 10$^5$ cases at-risk population, respectively. The number of MRD due to O$_3$ exposure in Ahvaz (Iran) with population higher than 1.3 million was 6.17 for people with ages $\geq$ 30 year-old (Karimi et al., 2019). In Surat (India), 24 HA-CVD, 1 MRD, and 4 LT-MRD per 10$^5$ people were attributed to O$_3$ exposure in 2018 (Jariwala and Kapadia, 2022).

Fig. 5 show more detailed the health effects estimation in Khorramabad due to O$_3$ exposure at different concentration intervals between

---

**Fig. 3.** The O$_3$ spatiotemporal variations in Iran during three monthly periods; before (21st February to March 21, 2020), during (22nd March to April 21, 2020), and after (22nd April to May 21, 2020) COVID-19 lockdown.

**Fig. 4.** Spatial distribution of O$_3$ concentrations before (21st February to March 21, 2020), during (22nd March to April 21, 2020), and after (22nd April to May 21, 2020) COVID-19 lockdown in Khorramabad, Iran.
years 2019–2021. The number of estimated cases according to RR distribution (95% confidence interval) for different concentration classes were obtained (Tables S2–S4). The highest attributable number was observed at higher O₃ levels, however the 80–89 ppb interval resulted in a higher exposure, therefore to more attributable cases of HA-CVD, MRD, and LT-MRD. The highest HA-CVD, MRD, and LT-MRD was estimated in 2020, due to higher O₃ concentrations.

In Tehran, in an annual mean 20.3 ppb, 272 HA-CVD due to O₃ exposure was calculated by AirQ software in 2015–2016 (Hadei et al., 2017a). The premature respiratory diseases mortality of O₃ exposure was equal to 7.16 in Hamadan in Iran (Asl et al., 2018). In Portugal, the estimated health effects due to exposure to O₃ among under exposed population depicted that MRD = 242 cases in 2013, and decreased to 143 cases in 2019 (Brito et al., 2022). In China, a study showed that LT-MRD increased by 0.55% for each 5 ppb increase in the daily maximum 8-h mean concentration of ambient O₃ (Zhang et al., 2021). The mean of premature deaths due to exposure by O₃ pollution in the Hainan Island (China) was reported 391 (95%CI: 212–570) person as annually (Li et al., 2020a).

4. Conclusion

In the current study, we investigated the trends of O₃ levels during COVID-19 lockdown in Iran and Khorramabad city by using spatio-temporal variation, and attributable health risks including HA-CVD, MRD, and LT-MRD related to O₃ exposure from 2019 to 2021. Between 2019 and 2021, the annual O₃ mean concentrations ranged from 14.1 to 15.8 ppb. The number of COVID-19 cases was negatively correlated to surface O₃ levels ($r = -0.59$, $p < 0.05$). The results showed rising O₃ levels during 2020, led to a higher number of O₃-related diseases (+60.6%, +14.8%, and +52.9% for HA-CVD, MRD, and LT-MRD, respectively). The higher levels of O₃ in 2020 is a noticeable factor contributing to higher number of mortality and morbidity compared to 2019 and 2021.

In Iran, there is no valuable law for control of air pollution emissions from the industries, road traffic, and fossil fuel burning. Monitoring and enforcing are outside the government’s power. In order to obtain policy response and the establishment of relevant policies for human health protection in Iran, we have to explore technological innovations such as monitoring by satellite, and provide more information about the links between air pollutants and health issues at local and national levels. Our results allow better knowledge and understanding about changes of O₃ concentrations during pandemic and its effect on human health.

Undergoing the rise in the emissions from anthropogenic activities as precursors of ground-level O₃, the number of cardiovascular and respiratory mortality per year increased in the different areas, while the land cover changes e.g., by increasing the vegetation and greenspace density may decline the effect of emission-driven related health; however, climate change especially global warming intensifies furtherly those impacts. Such outcomes highlight the emission control strategies associated with air oxidants such as O₃ can helps to reduce environmental pollution and public health issues (Fu and Tai, 2015).

Although our study has performed by the valuable methodology proposed by the WHO, but there are still limitations (Khaniabadi and Sicard, 2021). Due to unavailability information for interactions between different air pollutants, the health effect studies are generally
focused on a single pollutant. Similar studies only reflect exposure to a specified outdoor air pollutants while people commonly spend more time indoors (Guan et al., 2021). In general, this recommended model assumes that exposure to air pollution concentration measured at the monitoring stations are representative to all people living within a certain city at the same time (Guan et al., 2021; Khaniabadi et al., 2017c).

Author statement

Khatereh Anbari: project administration, designed research, and funding acquisition, Yusef Omidi Khaniabadi: methodology, writing original draft, data curation and analysis, and writing-review and editing, Pierre Sicard: validation, writing-review, and editing, Hasan Raja Naqvi: software, and created the figures, Rajab Rashidi: monitoring, data collection, and designed research. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study has supported been by the Lorentan University of Medical Sciences (IR.LUMS.REC.1400.184).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apr.2022.101600.

References

Abdolzadeh, A., Jafari, N., Mohammadi, A., Miri, M., Hajizadeh, Y., 2018. Mortality and morbidity due to exposure to ambient NO2, SO2 and O3 in Isfahan in 2013-2014. Int. J. Prev. Med. 9.
Adebayo-Ojo, T.C., Wichmann, J., Arowosegbe, O.O., Probst-Hensch, N., Schindler, C., Adebayo-Ojo, T.C., Wichmann, J., Arowosegbe, O.O., Probst-Hensch, N., Schindler, C., 2018. Mortality and morbidity due to exposure to ambient PM10 in the western cities of Iran. Toxic Rev. 37, 313–318.
Agathokleous, E., Feng, Z., Oksanen, E., Sicard, P., Wang, Q., Saitanis, C.J., 2021. Temporal incidence and prevalence of bronchitis and morbidities from short-term exposure to O3, NO2, and their combined oxidative potential on short-term exposure to O3, NO2, and their combined oxidative potential in Cape Town, South Africa, 2006–2015. Int. J. Environ. Res. Public Health 19, 8078.
Amoatey, P., Khaniabadi, Y.O., Sicard, P., Siddiqi, S.A., De Marco, A., Sulaiman, H., 2020. Long-term Trend of Ambient Air PM10, PM2.5 and O3 and Their Health Effects in Tabriz City, Iran, during 2006-2017. Sustainable Cities and Society.
Amoatey, P., Khaniabadi, Y.O., Sicard, P., Siddiqi, S.A., De Marco, A., Sulaiman, H., 2020. Long-term Trend of Ambient Air PM10, PM2.5 and O3 and Their Health Effects in Tabriz City, Iran, during 2006-2017. Sustainable Cities and Society.
Araminiene, V., Blande, J.D., Hayes, F., Calatayud, V., 2020. Ozone affects plant, biodiversity. Sci. Adv. 6, eabc1176.
Areh, M., Goudarzi, G., Rashidi, R., Keishams, F., Hopke, P.K., Mohammadi, M.J., 2021. Long-term health impacts attributed to ambient PM10 in the most polluted region during COVID-19 lockdown in Spain: a multi-city study. J. Environ. Sci. 101, 16–20.
Broomandi, P., Crape, B., Jahanbakhshi, A., Janatian, N., Nikfak, A., Tamjidi, M., Kim, J. R., Middeton, N., Karaca, F. 2022. Assessment of the association between dust storms and COVID-19 Infection rate in southwest Iran. Environ. Sci. Pollut. Control Ser. 1–20.
Broomandi, P., Karaca, F., Nikfak, A., Jahanbakhshi, A., Tamjidi, M., Kim, J., 2020. Impact of COVID-19 event on the air quality in Iran. Aerosol Air Qual. Res. 20, 1793–1804.
Burnett, R.T., Pope III, C.A., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shih, H.H., Singh, G., Hubbell, B., Brauer, M., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ. Health Perspect. 122, 397–403.
Carballo-Royo, L., Miranda-Soberanis, V., Medina-Ramon, M., Rojas-Bracho, L., 2015. Effect of PM2.5 on infant mortality in the State of Puebla in the south of Mexico. Environ. Health: Int. J. Monit. 14, 57.
Chen, K., Wang, P., Zhao, H., Wang, P., Gao, A., Mylllyvirta, L., Zhang, H., 2021. Summertime O3 and related health risks in the north China plain: a modeling study using two anthropogenic emission inventories. Atmos. Environ. 246, 118087.
Chen, L.-W.A., Chien, L.-C., Li, Y., Lin, G., 2020. Nonuniform impacts of COVID-19 lockdown on air quality over the United States. Sci. Total Environ. 745, 141105.
Chen, M.-W.A., Goudarzi, G., Rashidi, R., Keishams, F., Hopke, P.K., Mohammadi, M.J., 2021. Long-term health impacts attributed to ambient PM10 in the most polluted region during COVID-19 lockdown in Spain: a multi-city study. J. Environ. Sci. 101, 16–20.
Chen, K., Wang, P., Zhao, H., Wang, P., Gao, A., Mylllyvirta, L., Zhang, H., 2021. Summertime O3 and related health risks in the north China plain: a modeling study using two anthropogenic emission inventories. Atmos. Environ. 246, 118087.
Chen, L.-W.A., Chien, L.-C., Li, Y., Lin, G., 2020. Nonuniform impacts of COVID-19 lockdown on air quality over the United States. Sci. Total Environ. 745, 141105.
Daryanoosh, M., Goudarzi, G., Rashidi, R., Keishams, F., Hopke, P.K., Mohammadi, M.J., 2021. Long-term health impacts attributed to ambient PM10 in the western cities of Iran. Toxic Rev. 37, 313–318.
De Marco, A., Amoatey, P., Khaniabadi, Y.O., Sicard, P., Hopke, P.K. 2018. Mortality and morbidity for cardiopulmonary diseases attributed to PM2.5 exposure in the metropolitan of Rome, Italy. Eur. J. Intern. Med. 57, 49–57.
Fattore, E., Paiano, V., Bertoldi, M., Cosmi, P., Fattore, E., Paiano, V., Bertoldi, M., Cosmi, P., 2020. PM2.5 impacts on health. Environ. Res. 211, 113048.
Fujita, M., Momeniha, F., Gholampour, A., Hassanvand, M.S., 2018. Long-term trends and health impact of PM2.5 and O3 in Tehran, Iran. 2006-2015. Environment international 114, 37–49.
Furo, Y., Tai, A., 2015. Impact of climate and land cover changes on tropospheric ozone air quality and public health in East Asia between 1980 and 2010. Atmos. Chem. Phys. 15, 10093–10106.
Guan, Y., Xiao, Y., Rong, B., Zhang, N., Chu, C., 2021. Long-term health impacts due to chronic exposure to PM2.5 in 10 cities of Iran (2013-2015); an epidemiological study. Environ. Health Perspect. 122, 3971–3978.
Hadei, M., Nazari, S.S.H., Eslami, A., Khosravi, A., Yarahmadi, M., Naghdali, Z., 2021. Long-term health impacts due to chronic exposure to PM2.5 in 10 cities of Iran (2013-2015); an epidemiological study. Environ. Health Perspect. 122, 3971–3978.
Hadi, M., Hopke, P.K., Nazari, S.S.H., Yarahmadi, M., Shashavani, A., Alipour, M.R., 2017a. Estimation of mortality and hospital admissions attributed to criteria air pollutants in Tehran metropolitan, Iran. Aerosol Air Qual. Res. 17, 2474–2481.
Hadi, M., Nazari, S.S.H., Eslami, A., Khosravi, A., Nazari, S.S.H., Eslami, A., Khosravi, A., 2017b. Air pollution and residential residents in a modeling study. J. Environ. Health 12, 351–357.
Hashim, B.M., Al-Naseri, S.K., Al-Malki, A., Al-Namari, A., 2021. Impact of COVID-19 lockdown on NO2, PM2.5 and PM10 concentrations and assessing air quality changes in Baghdad, Iraq. Sci. Total Environ. 754, 141978.
Heron, L., Anderson, H.A., Fitchett, R., Mohamed, A., Cohen, A., Forastiere, F., Hurley, L., Ryter, G., Krewski, D., Krzywinska, M., 2015. Quantifying the health impacts of the global urban air pollution epidemic due to ambient PM2.5. Environ. Health Perspect. 123, 46–53.
Khatereh Anbari, K., Sicard, P., Omidi Khaniabadi, Y., Raja Naqvi, H., Rashidi, R., 2021. Long-term Trend of Ambient Air PM10, PM2.5 and O3 and Their Health Effects in Tabriz City, Iran, during 2006-2017. Sustainable Cities and Society.
health impacts of ambient air pollutants: recommendations of a WHO/Europe project. Int. J. Publ. Health 60, 619–627.

Higham, J., Ramirez, C.A., Green, M.J., Moere, A., 2021. UK COVID-19 lockdown: 10 days of air pollution reduction? Air Quality, Atmosphere & Health 14, 325–332.

Jariwala, N., Kapadia, D., 2022. Estimation of health impact using AirQ+ model attributed to surface ozone in sub-regions of Surat city, India. Journal of Air Pollution Assessment and Health 7, 247–260.

Jeong, S.J., 2013. The impact of air pollution on human health in Suwon City. Asian journal of atmospheric environment 7, 227–233.

Karimi, A., Shirmardi, M., Hadeie, M., Birgani, Y.T., Neisi, A., Taklastan, A., Goudarzi, G., 2019. Concentrations and health effects of short- and long-term exposure to PM2.5, NO2, and O3 in ambient air of Ahvaz city, Iran (2014–2017). Ecotoxicol. Environ. Saf. 180, 542–548.

Kerimray, A., Baimaqal, N., Bregimova, O.P., Bukovem, B., Koresnov, F., Plotynch, P., Karaca, F., 2020. Assessing air quality changes in large cities during COVID-19 lockdowns: the impacts of traffic-free urban conditions in Almaty, Kazakhstan. Sci. Total Environ. 730, 139179.

Khaniabadi, Y.O., Daryanosh, S.M., Amran, A., Polosa, R., Hopke, P.K., Goudarzi, G., Mohammadi, M.J., Sicard, P., Armin, H., 2017a. Impact of Middle eastern dust storms on human health. Atmos. Pollut. Res. 8, 606–613.

Khaniabadi, Y.O., Goudarzi, G., Daryanosh, S.M., Bergini, A., Tittarelli, A., De Marco, A., 2017b. Exposure to PM10, NO2, and O3 and impacts on human health. Environ. Sci. Pollut. Control. 24, 2781–2789.

Khaniabadi, Y.O., Sicard, P., 2021. A 10-year assessment of ambient fine particles and related health endpoints in a large Mediterranean city. Chemosphere 278, 130502.

Khaniabadi, Y.O., Sicard, P., Khaniabadi, A.O., Mohammadinejad, S., Keishehs, F., Taklastan, A., Najafi, A., De Marco, A., Daryanosh, M., 2019a. Air quality modeling for health risk assessment of ambient PM10, PM2.5 and SO2 in Iran. Human and Ecological Risk Assessment. Int. J. 125, 2988–3019.

Khaniabadi, Y.O., Sicard, P., Taklastan, A., Hopke, P.K., Taiwo, A.M., Khaniabadi, F.O., De Marco, A., 2019b. Mortality and morbidity due to ambient air pollution in Iran. Clinical Epidemiology and Global Health 7, 222–227.

Landrigan, P.J., Fuller, R., Acosta, N.J., Adey, O., Arnold, R., Balde, A.B., Bertolino, R., Bone-O’Reilly, S., Boufford, J.J., Breyse, P.N., 2018. The Lancet Commission on pollution and health. Lancet 391, 260–280.

Li, A., Pei, L., Zhao, M., Xu, J., Mei, Y., Li, R., Xu, Q., 2019. Investigating potential associations between O3 exposure and lipid profiles: a longitudinal study of older adults in Beijing. Environ. Int. 133, 105135.

Lin, X., Cao, X., Guo, M., Xie, M., Liu, X., 2020b. Trends and Risk Factors of Mortality and Disability Adjusted Life Years for Chronic Respiratory Diseases from 1990 to 2017: Systematic Analysis for the Global Burden of Disease Study, p. 368, 2017.

Makushkina, E., Becker, J.S., Serre, M.L., West, J.J., Chang, K.-L., Liu, H., Liu, S., Xue, B., Lv, Z., Meng, Z., Yang, X., Xue, T., Yu, Q., He, K., 2017. Impact of O3 pollution and health impacts in Iranian megacity. Stoch. Environ. Res. Risk Assess. 1–10.

Rovira, J., Domingo, J.L., Schuhmacher, M., 2020. Air quality, health impacts and burden of disease due to air pollution (PM10, PM2.5, NO2 and O3): application of AirQ+ model to the Camp de Tarragona County ( Catalonia, Spain). Sci. Total Environ. 703, 135538.

Schwarz, L., Hansen, K., Alari, A., Iango, S.D., Bernal, N., Banu, R., Gershunov, A., Jemmariena, T., 2021. Spatial variation in the joint effect of extreme heat events and ozone on respiratory hospitalizations in California. Proc. Natl. Acad. Sci. USA 118, e2023078118.

Sicard, P., De Marco, A., Agathokleous, E., Feng, Z., Xu, X., Paletti, E., Rodriguez, J.D.R., Calatayud, V., 2020. Amplified ozone pollution in cities over the COVID-19 lockdown. Sci. Total Environ. 735, 139542.

Sicard, P., Khaniabadi, V.O., De Marco, A., 2019c. Effect of O3, PM10 and PM2.5 on cardiovascular and respiratory diseases in cities of France, Iran and Italy. Sci. Total Environ. Pollut. Control Ser. 26, 32645–32665.

Siciliano, B., Dantas, G., da Silva, C.M., Aribilla, G., 2020. Increased ozone levels during the COVID-19 lockdown: analysis for the city of Rio de Janeiro, Brazil. Sci. Total Environ. 737, 139765.

Stafoggia, M., Otelfad, B., Chen, J., Rodopoulou, S., Renzi, M., Atkinson, R.W., Balmes, J., Miquel-Jurado, E., Bos, B., 2020. Mortality and morbidity due to ambient air pollution during COVID-19 lockdown: a systematic review and meta-analysis. Int. J. Publ. Health 66, e201900254.

Tobias, A., Carneiro, C., Reche, C., Managul, J., Vio, M., Mingüillón, M.C., Alastuey, A., Querol, X., 2020. Changes in air quality during the lockdown in Barcelona (Spain) one month behind the SARS-CoV-2 epidemic. Sci. Total Environ. 726, 138540.

Vega, E., Nandez, A., Bronswell, M., Miquel-jurado, R., Reisend-martinez, C., Jaimes-palmera, M., Luna-falitas, F., Ferrazan-abuhamd, A., Maja, K.J., Entwistle, J., 2021. Changes in air quality in Mexico City, London and Delhi in response to various stages and levels of lockdowns and easing of restrictions during COVID-19 pandemic. Environ. Pollut. 285, 117664.

Vinikoor-Imler, L.C., Owens, E.O., an, F., Lang, J., 2021. The Effect of pm2.5 pollution and health impacts in China. Atmospheric Environment .

Wang, H., Miao, Q., Shen, L., Yang, Q., Wu, Y., Wei, H., 2021a. Air pollutant variations in Suzhou during the 2019 novel coronavirus (COVID-19) lockdown of 2020: high time-resolution measurements of aerosol chemical compositions and source apportionment. Environ. Pollut. 271, 116298.

Wang, H., Tan, Y., Zhang, L., Shen, J., Zhao, T., Dai, Q., Guan, T., Ke, Y., Li, X., 2021b. Characteristics of air quality in different climatic zones of China during the COVID-19 lockdown. Atmos. Pollut. Res. 12, 101247.

Yang, Z., Ma, Y., Feng, F., Cheng, B., Shen, J., Wang, H., Jiao, H., Li, M., 2021. Respiratory mortality associated with ozone in China: a systematic review and meta-analysis. Environ. Pollut. 280, 116957.

Zhao, N., Pinault, L., Toyib, O., Vanos, J., Tjepkema, M., Cakmak, S., 2021. Long-term exposure to low ambient air pollution concentrations and mortality among 28 million people: results from seven large European cohorts within the ELAPSE project. Lancet Planet. Health 6, e9–e18.

Zhang, Y., Ma, Y., Feng, F., Cheng, B., Shen, J., Wang, H., Jiao, H., Li, M., 2021. Respiratory mortality associated with ozone in China: a systematic review and meta-analysis. Environ. Pollut. 280, 116957.