



# Ambient PM<sub>2.5</sub> and O<sub>3</sub> pollution and health impacts in Iranian megacity

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## Abstract

The main objectives of this study were to (i) assess variation within fine particles (PM<sub>2.5</sub>) and tropospheric ozone (O<sub>3</sub>) time series in Khorramabad (Iran) between 2019 (before) and 2020 (during COVID-19 pandemic); (ii) assess relationship between PM<sub>2.5</sub> and O<sub>3</sub>, the PM<sub>2.5</sub>/O<sub>3</sub> ratio, and energy consumption; and (iii) estimate the health effects of exposure to ambient PM<sub>2.5</sub> and O<sub>3</sub>. From hourly PM<sub>2.5</sub> and O<sub>3</sub> concentrations, we applied both linear–log and integrated exposure–response functions, city-specific relative risk, and baseline incidence values to estimate the health effects over time. A significant correlation was found between PM<sub>2.5</sub> and O<sub>3</sub> ( $r = -0.46$  in 2019,  $r = -0.55$  in 2020,  $p < 0.05$ ). The number of premature deaths for all non-accidental causes (27.5 and 24.6), ischemic heart disease (7.3 and 6.3), chronic obstructive pulmonary disease (17 and 19.2), and lung cancer (9.2 and 6.25) attributed to ambient PM<sub>2.5</sub> exposure and for respiratory diseases (4.7 and 5.4) for exposure to O<sub>3</sub> above 10 µg m<sup>-3</sup> for people older than 30-year-old were obtained in 2019 and 2020. The number of years of life lost declined by 11.6% in 2020 and exposure to PM<sub>2.5</sub> reduced the life expectancy by 0.58 and 0.45 years, respectively in 2019 and 2020. Compared to 2019, the restrictive measures associated to COVID-19 pandemic led to reduction in PM<sub>2.5</sub> (–25.5%) and an increase of O<sub>3</sub> concentration (+ 8.0%) in Khorramabad.

**Keywords** Air pollution · Health effect · PM<sub>2.5</sub> · O<sub>3</sub> · COVID-19

## Abbreviations

RR	Relative risk
BI	Baseline incidence
AP	Attributable proportion
NC	Number of cases
NE	Number of excess cases
SOMO35	Sum of O <sub>3</sub> means over 35 ppb
RD	Respiratory diseases
COPD	Chronic obstructive pulmonary disease
LC	Lung cancer

IHD	Ischemic heart disease
IER	Integrated exposure–response
YLL	Years of life lost
ELR	Expected life remaining

## 1 Introduction

Air pollution due to industrialization, urbanization, and population growth is one of the global health issue in the last century (Guan et al. 2016; Landrigan et al. 2018; Neira 2019), especially in developing Middle Eastern countries characterized by dust storms such as Iran (Farzadfar et al. 2022). Therefore, numerous epidemiological studies were conducted about chronic and acute effects of exposure of population to ambient air pollutants (Ostro et al. 2018; Toe et al. 2021). Particulate matters (PM<sub>2.5</sub> and PM<sub>10</sub>), tropospheric ozone (O<sub>3</sub>) and nitrogen dioxide (NO<sub>2</sub>) are among the most threatening air pollutants in cities with harmful effects on human health (De Marco et al. 2018; Sicard et al. 2019; Mannucci 2022). Previous studies have reported a strong association between exposure to air pollutants (PM<sub>2.5</sub>,

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PM<sub>10</sub>, O<sub>3</sub> and NO<sub>2</sub>) and cardiovascular and respiratory diseases, and premature mortality (Anderson 2009, Khaniabadi et al. 2018a, Hashemzadeh et al. 2019, Khomenko et al. 2021, Liu et al. 2021, Zhao et al. 2021). Among these air pollutants, PM<sub>2.5</sub> and O<sub>3</sub> led to e.g., increased cardiorespiratory deaths, asthma exacerbation, and hospital admissions for cardiovascular and respiratory diseases (Christakos and Kolovos 1999; Crouse et al. 2015; Goodman et al. 2015; Amoatey et al. 2019; Yazdi et al. 2019; Sicard et al. 2020). The PM<sub>2.5</sub> is linked to increases in respiratory problems, cardiovascular health effects, risk of lung cancer and premature mortality. Climate change and air pollution are closely linked (Sicard et al. 2016a, De Marco et al. 2022a, b) since the source of greenhouse gases and air pollutants are generally similar (O'Donovan et al. 2018; De Marco et al. 2022b). Ozone is the third most important greenhouse gas in terms of radiative forcing, contributing to climate change (Amoatey et al. 2019). Due to the human activities like industrial processing, transportation and energy consumption, the O<sub>3</sub> levels increased in the last decades in cities (Siciliano et al. 2020; Zoran et al. 2020; De Marco et al. 2022a), and this increase in cities was intensified during the COVID-19 lockdown (Siciliano et al. 2020; Zoran et al. 2020; Sicard et al. 2020) with negative impacts on human and ecosystems health (Wang et al. 2020; Shin et al. 2021). Research on ambient PM<sub>2.5</sub> and O<sub>3</sub> and their health effects is conducted in cities such as New York (Kheirbek et al. 2013), Beijing (Xie et al. 2019), Delhi (Amann et al. 2017), Paris (Bressi et al. 2013), Los Angeles (Hasheminassab et al. 2014), Lisbon (Garrett and Casimiro 2011), Rome (Sicard et al. 2019), and Catalonia (Rovira et al. 2020). In Iran, some studies were performed in Ahvaz (Karimi et al. 2019), Tabriz (Barzeghar et al. 2020), Tehran (Faridi et al. 2018), and Shahrekord (Naghan et al. 2022) to assess the effects of PM<sub>2.5</sub> and O<sub>3</sub> on mortality and morbidity among population. Southwest of Iran (Lorestan Province) has experienced elevated air pollution due to Middle East Dust (MED) storms, road traffic, and increased industrial operations. In recent years, Khorramabad has witnessed similar high exposure to ambient air pollutants such as PM<sub>2.5</sub> and O<sub>3</sub>. The main objectives of the present study were to investigate the health effects of PM<sub>2.5</sub> and O<sub>3</sub> by concentration–response model, and estimate the years of life lost and loss of life expectancy in 2019 and 2020 in Khorramabad, southwestern city of Iran.

## 2 Materials and methods

### 2.1 Study area

Khorramabad (33°48'N; 48°35'E), with a population of about 540,000 people, is located in Lorestan Province,

southwestern of Iran (Fig. 1). The annual mean precipitation and air temperature is 511 mm and 19.2 °C, respectively. Khorramabad is classed under the Köppen climate classification as a hot-summer Mediterranean climate (Daryanoosh et al. 2018). In this region, the main causes of air pollution are the dust storms leading to high concentrations of particulate matters (Kianisadr et al., 2018). In addition, petrochemical industries and road traffic emissions have exacerbated the poorly air quality (Daryanoosh et al. 2018, Kianisadr et al., 2018). The city is surrounded by the high Zagros Mountains (1170 m a.s.l) trapping the ambient air pollutants within the atmospheric boundary layer leading to higher pollution levels (Daryanoosh et al. 2018).

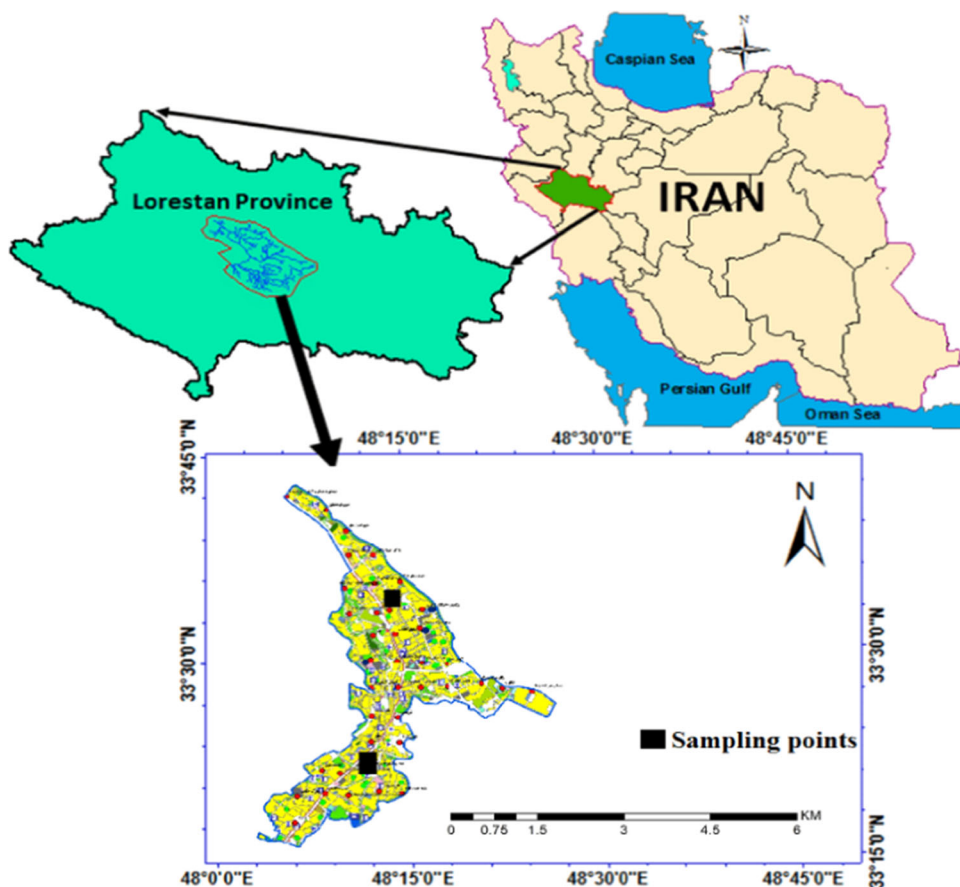
### 2.2 Data collection

The hourly PM<sub>2.5</sub> and O<sub>3</sub> concentrations were obtained, from 1st January 2018 to 31st December 2021, from two urban monitoring stations provided by the local Environment Protection Agency under the Iranian Department of Environment (<https://www.doe.ir>). Then, the hourly data were aggregated to daily averages with at least 75% validated hourly data or non-missing values using Microsoft Excel Package (Khaniabadi and Sicard 2021b).

### 2.3 Data processing

In this study, we detected outliers within time-series by using Z-scores. The standard cut-off value for finding outliers are Z-scores of  $\pm 3$ . The PM<sub>2.5</sub>/O<sub>3</sub> ratio was calculated to fully understand the relationship between PM<sub>2.5</sub> and O<sub>3</sub>. This applied ratio can be used as an indicators of air pollution over time to describe the underlying atmospheric processes and to provide further understanding of the spatio-temporal variability of air pollutants. In the risk assessment, exposure is considered equal to air pollutants concentrations at a specific point in space and time (Bogaert et al. 2009; Neisi et al. 2018, Khaniabadi and Sicard 2021b). The concentration–response (C-R) model was developed from current systematic reviews and meta-analysis of various short- and long-term mortality and morbidity health effects for air pollution exposure. For the analysis of exposure by air pollutant, the baseline incidence (BI), relative risk (RR) and the number of people at risk (N) over an area are needed. The BI is the rate of incidence of given health effect in an exposed population and the RR is derived from different published papers and represent the chance of developing air pollution related diseases as a result of exposure per each 10  $\mu\text{g m}^{-3}$  increase in the air concentration (Sicard et al. 2019). The RR measures the probability of developing a disease related to exposure based on Eq. 1.

**Fig.1** The study area of Khorramabad, Iran



$$RR = \exp[\beta * (X - X_0)] \tag{1}$$

where  $\beta$  is a parameter which regulates the amount of RR increasing,  $X$  and  $X_0$  ( $\mu\text{g m}^{-3}$ ) also are respectively the measured air pollutant concentrations and background where no health effect recorded (De Marco et al. 2018).

For the quantification of mortality related to ischemic heart disease, chronic obstructive pulmonary disease and lung cancer, integrated exposure–response functions from European cohort studies can be used (Eq. 2).

$$\left\{ \begin{array}{l} \text{if } z \geq z_{cf} \text{ then } RR(z) = 1 + \alpha \{ 1 - \exp[-\gamma * (z - z_{cf}) * \delta] \} \\ \text{if } z < z_{cf} \text{ then } RR(z) = 1 \end{array} \right\} \tag{2}$$

where  $z$  and  $z_{cf}$  are respectively the annual mean concentration and the counterfactual  $\text{PM}_{2.5}$  concentration below which we assume no additional risk. Also, parameters  $\alpha$ ,  $\gamma$  and  $\delta$  are pre-integrated (De Marco et al. 2018; Al-Hemoud et al. 2020; Amoatey et al. 2020; Rovira et al. 2020). Furthermore, the Attributable Proportion (AP %) is the fraction of a health effect that can be statistically associated with the exposure to the air pollutant,  $c$ , in a population  $P(c)$  (Eq. 3).

$$AP = \frac{\sum ([RR(c) - 1] * P(c))}{\sum [RR(c) * P(c)]} \tag{3}$$

where AP is the attributable proportion of the health effect,  $RR(c)$  is the relative risk for certain health impacts in category “ $c$ ” (e.g., residential, or industrial) of exposure obtained from exposure–response functions derived from epidemiological studies (Hadei et al. 2017; Rovira et al. 2020).  $P(c)$  is number of individuals at risk (Gurjar et al. 2010; Fattore et al. 2011; Daryanoosh et al. 2017; Khaniabadi et al. 2017a).

For a health effect, the number of cases  $NC_c$  per 100,000 people at risk attributed to the air pollutant  $c$  is calculated as  $NC_c = BI * AP$ . The number of excess cases,  $NE_c$ , attributed to the air pollutant  $c$  is calculated as  $NE_c = 10^{-5} * [NC_c * N]$ , where  $N$  is the number of people at risk exposed to the air pollutant  $c$  (De Marco et al. 2018).

SOMO35 (Sum of Ozone Means Over 35 ppb) is a metric for health impact assessment, based on recent epidemiological studies, and recommended by WHO (Aksoyoglu et al. 2014). SOMO35 (in  $\mu\text{g m}^{-3}$  days) is defined as the yearly sum of the daily maximum of 8-h running average for  $\text{O}_3$  over 35 ppb (i.e.,  $70 \mu\text{g m}^{-3}$ ) was calculated (Eq. 4).

$$SOMO35 = \sum_i \max * [0.(C_i - 70)] \quad (4)$$

where  $C_i$  is the maximum daily  $O_3$  mean concentrations (in  $\mu\text{g m}^{-3}$ ), and  $i$  number of days in a calendar year. Since SOMO35 is sensitive to missing daily  $O_3$  concentrations, it is corrected to full annual coverage with actual valid daily concentration levels ( $N_{\text{valid}}$ ) according to below equation (Eq. 5).

$$SOMO35 = SOMO35_{\text{uncorrected}} * N_{\text{total}}/N_{\text{valid}} \quad (5)$$

where,  $N_{\text{total}}$  = total number of days in a calendar year (365 days in 2019, 366 in 2020),  $N_{\text{valid}}$  = total validated daily  $O_3$  mean concentration.

The long-term effects on mortality due to respiratory diseases, according to RR functions, is shown in Eq. 6 for each  $10 \mu\text{g m}^{-3}$  increase in  $O_3$  levels. It is modeled as a log-linear function.

$$RR = \exp\{\beta.SOMO35_{\text{uncorrected}}/N_{\text{valid}}\} \quad (6)$$

Similarly, for mortality due to respiratory diseases from  $O_3$  exposure, the model estimates the integrated exposure–response (IER) function by Eq. 7.

$$RR = \exp[\beta.\{C_{\text{max}8} - X_0\}] \quad (7)$$

where  $\beta$  is the increase rate of RR.  $C_{\text{max}8}$  ( $\mu\text{g m}^{-3}$ ) is the maximum average daily 8-h  $O_3$  concentrations and  $X_0$  is daily concentration of  $O_3$ .

The BI is the rate of incidence of a given health outcome in the population. As recommended by WHO, to estimate mortality due to respiratory diseases (M-RD) and all-causes mortality (M-all-cause) attributable to the long-term exposure to  $PM_{2.5}$ , we used linear-log function, respectively. Besides, to assess the cause-specific mortality in adults, including ischemic heart disease (M-IHD), chronic obstructive pulmonary disease (M-COPD) and lung cancer (M-LC) among adults more than 30-year-old attributable to  $PM_{2.5}$  exposure, we used the IER function as are described by (Burnett et al. 2014; Héroux et al. 2015; Faridi et al. 2018). Following the International Statistical Classification of Diseases and Related Health Problems 10th Revision (ICD-10), J95 and J96 are associated to respiratory mortality, J120-J189, J209-J499, and J690-J700 and J44 codes are associated to COPD, C33 and C34 are correspond to LC, and codes I20 to I25 are related to IHD. Table 1 shows the year-specific BI amounts used in this study for assess of health effects attributed  $PM_{2.5}$  and  $O_3$  in Khorramabad, Iran.

## 2.4 Statistical estimation and years of life lost

Data were analyzed for normal distribution by the Kolmogorov–Smirnov one-sample D-test. The correlation

analyses were performed by using the Pearson regression between air pollutants concentrations from January 2019 to January 2020. To estimate the years of life lost (YLL), life table method is used (Hadei et al. 2020) as well as losses of expected life remaining (ELR) in a population. For this, rate of population and deaths are required. The loss of life expectancy using population-weighted was estimated.

## 3 Results and discussion

### 3.1 Temporal variability

In 2019 and 2020, the highest  $PM_{2.5}$  ( $133.6 \mu\text{g m}^{-3}$ ) and  $O_3$  ( $46.1 \mu\text{g m}^{-3}$ ) mean concentrations were recorded in 2019, while lower levels were observed in 2020 ( $89.7$  and  $37.7 \mu\text{g m}^{-3}$ , respectively). The annual  $PM_{2.5}$  mean concentration exceeded the 2021 WHO guideline value for human health protection ( $5 \mu\text{g m}^{-3}$ ), while  $O_3$  did not exceeded the daily 8-h annual mean guideline ( $100 \mu\text{g m}^{-3}$ ). Figure 2 shows the time series of  $PM_{2.5}$  and  $O_3$  level in 2019 (normal condition before COVID-19) and 2020 (during COVID-19 pandemic) in Khorramabad.

In this study, we observed the higher  $PM_{2.5}$  levels within cold season due to activities at home such as high combustion emissions, domestic heating, biomass burning (Amoatey et al. 2020) and dust storms (Amoatey et al. 2021; Goudarzi et al. 2021). In the southwest of Iran, there is encountered with the high levels of particles from MED storms with Arabians' desserts sources (Broomandi et al. 2022) which disperses more during winter season because of higher wind speed (Khaniabadi et al. 2017c, 2019; Omidi Khaniabadi et al. 2019). The  $O_3$  levels were higher during warm season due to transportation of air masses, emissions (Wu and Xie 2017), and photo-chemical reaction (Guo et al. 2017) Lei et al. 2019).

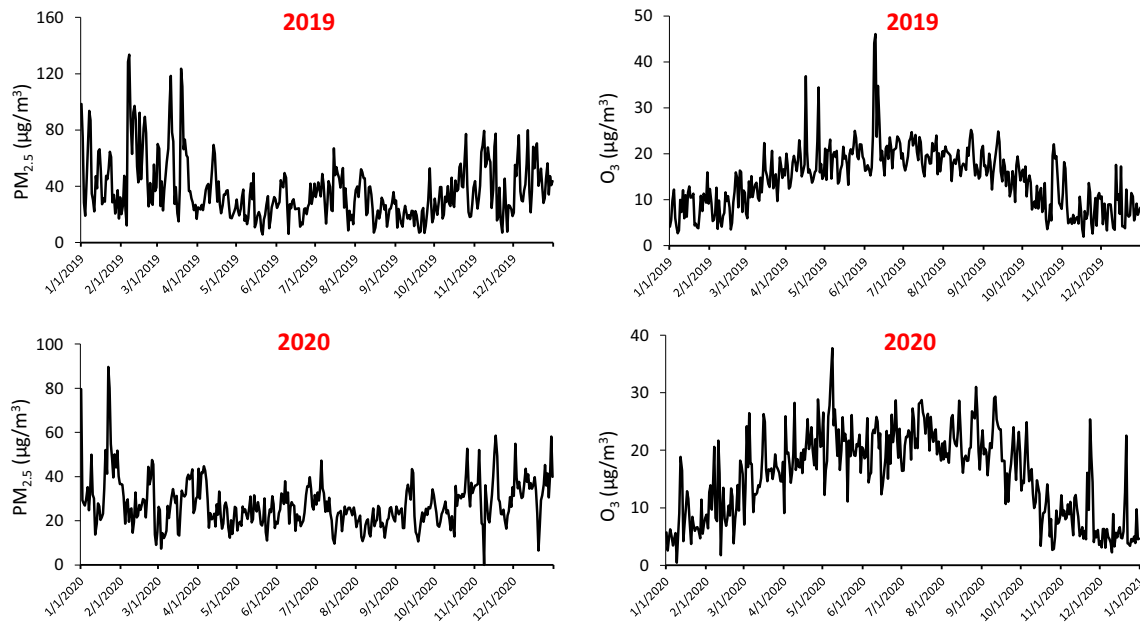
### 3.2 Relationship between $PM_{2.5}$ and $O_3$

The daily  $PM_{2.5}$  concentrations was well correlated to  $O_3$  in 2019 ( $r = -0.46$ ,  $p < 0.05$ ) and 2020 ( $r = -0.55$ ,  $p < 0.05$ ), with  $PM_{2.5}/O_3$  amounts about 4.1 and 2.9, respectively in these two years (Fig. 3). High PM levels leads to a reduced solar radiation (Li et al. 2017; Zhang et al. 2022) leading to a decrease of surface  $O_3$  formation (Khaniabadi and Sicard 2021a, Sicard 2021). Furthermore, the heterogeneous chemical processes occurring on  $PM_{2.5}$  surface with  $O_3$  are a way for  $O_3$  removal by  $PM_{2.5}$  in the atmosphere (Amoatey et al. 2019; Sicard et al. 2019).

Higher  $PM_{2.5}/O_3$  ratio in 2019 than 2020 showed the high contribution of traffic road (De Marco et al. 2018), fossil fuels consumption and dust storms (Naghan et al. 2022) leading to rising  $PM_{2.5}$  concentration in the air,

**Table 1** Baseline incidence (BI) and relative risk (RR) values for health outcomes, and people at risk at 95% confidence intervals (95% CI) for long-term exposure to PM<sub>2.5</sub> and O<sub>3</sub> concentrations (lag0-1 days) more than 10 µg m<sup>-3</sup>

Health outcomes	BI	RR per 10 µg m <sup>-3</sup> (95% CI)	Ref
<b>PM<sub>2.5</sub></b>			
Mortality, all-cause (age ≥ 30)	845–1832	1.062 (1.04–1.083)	Héroux et al. (2015)
Mortality, IHD (age ≥ 25)	101–177	IER function	Burnett et al. (2014)
Mortality, COPD (age ≥ 30)	13–20	IER function	Burnett et al. (2014)
Mortality, LC (age ≥ 30)	11–22	IER function	Burnett et al. (2014)
<b>O<sub>3</sub></b>			
Mortality, respiratory diseases (age ≥ 30)	44–53	1.014 (1.005–1.024)	Héroux et al. (2015)

**Fig. 2** Time series trends of PM<sub>2.5</sub> and O<sub>3</sub> levels in 2019 and 2020 in Khorramabad, Iran

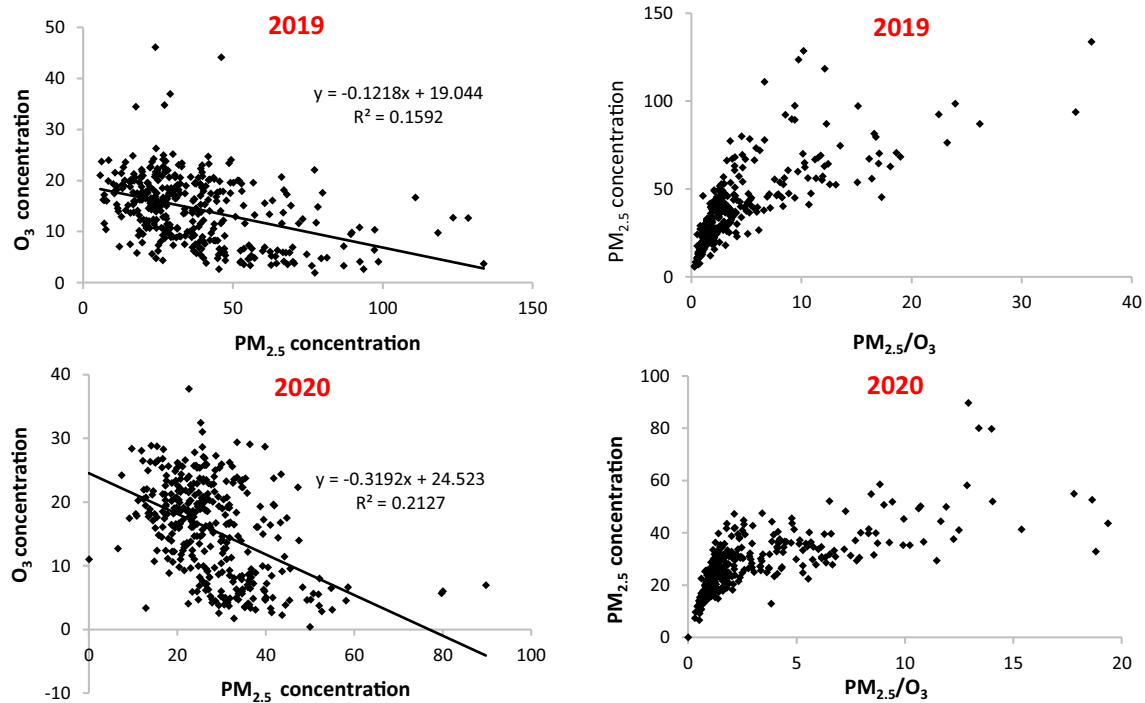
reducing solar radiation (Adhikari and Yin 2020). In 2020, COVID-19 lockdown, with restricted activities, led to a reduction in PM<sub>2.5</sub> concentrations and to higher O<sub>3</sub> levels (Sicard et al. 2020).

### 3.3 Comparison of mean pollutants and energy consumption

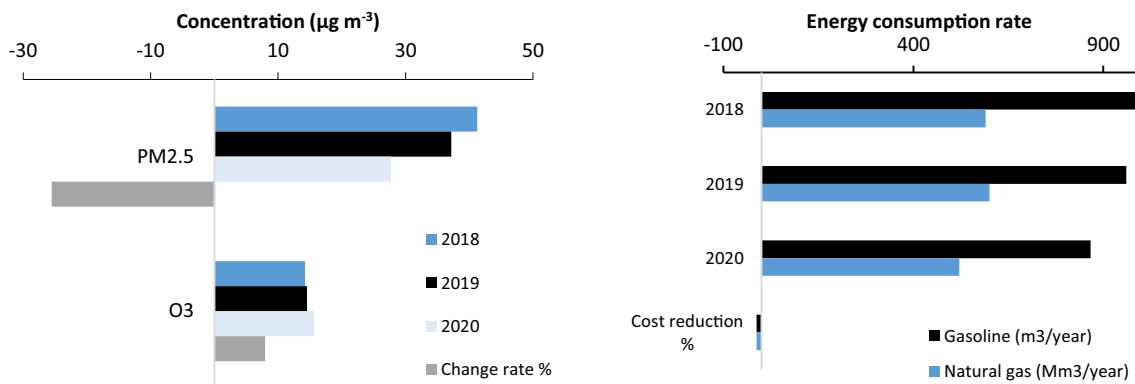
A comparison between the pre-COVID-19 pandemic and COVID-19 period for PM<sub>2.5</sub> and O<sub>3</sub> mean concentrations in 2018, 2019 and 2020 across Khorramabad, was investigated (Fig. 4). The first overview illustrated, restrictive measures in relation to COVID-19 pandemic led to a reduction in the annual average of PM<sub>2.5</sub> by—25.5%. Furthermore, the annual averages O<sub>3</sub> in 2020 compared to previous years increased by + 8.0% during COVID-19 year.

(Sicard et al. 2020) showed that O<sub>3</sub> increased in Wuhan, Valencia, Nice and Rome higher than previous years 2017–2019, while PM<sub>2.5</sub> annual averages was reduced in these cities during 2020. By considering long-time-series, a trends analysis in Marseille showed that the restrictive measures due to COVID-19 led to an actual reduction of 11% in PM<sub>2.5</sub> concentrations compared to the time period 2010–2019 (Khaniabadi and Sicard 2021b). Another study showed that O<sub>3</sub> was the only pollutant increased over the COVID pandemic, and then decreased by 20% post-COVID with government monitoring (Bhatti et al. 2021). In Almaty, Kazakhstan (Kerimray et al. 2020), the annual averages of PM<sub>2.5</sub> during 2019 and 2020 were respectively 40 and 31 µg m<sup>-3</sup>, in which the concentration was reduced during COVID-19 at 2020 almost—29%.

The yearly comparative of fuel consumption including gasoline and natural gas pre-pandemic (2018 and 2019)



**Fig.3** (left) Correlation between  $PM_{2.5}$  with  $O_3$  levels, and (right) relationship between  $PM_{2.5}/O_3$  ratio with  $PM_{2.5}$  during 2019 and 2020 across Khorramabad, Iran



**Fig.4** (left) Comparative bar between  $PM_{2.5}$  and  $O_3$  averages in 2018, 2019 (before COVID-19) with 2020 (during COVID-19), and (right) Cost reduction in fuel consumption in 2018, 2019 (before COVID-19) with 2020 (during COVID-19) across Khorramabad, Iran

and during-COVID-19 (2020) showed a lowering in the cost of consumption fuels during the COVID-19. The variation rate for gasoline ( $m^3 \text{ year}^{-1}$ ) and natural gas (in  $Mm^3 \text{ year}^{-1}$ ) lead to a reduction in cost for people about  $-13.06\%$  and  $-12.56\%$ , respectively in 2020 (Fig. 4). There was a positive association between  $PM_{2.5}$  concentration and gasoline and natural gas consumption ( $p < 0.05$ ), while a negatively association with  $O_3$  concentration ( $p < 0.05$ ) was performed.

The cost-reduction indicates that the higher air quality has a positive association with human activity, lower traffic and the closure of factories which all causes reduce consumption of energy (Tian et al. 2021) and provides a better

air quality (Agami and Dayan 2021) in the different areas within the world. A comparative study on fuel consumption in Israel indicated that with extensive COVID-19 in the world, the consumption of gasoline and natural gas was reduced  $-22.5\%$  and  $-10\%$  respectively than the same period within 2019. In Turkey, (Güngör et al. 2021) demonstrates gasoline consumption during COVID-19 was lower than the same time in 2019.

### 3.4 Health impact of PM<sub>2.5</sub> and O<sub>3</sub> and the years of life lost

The number of premature deaths for non-accidental causes for PM<sub>2.5</sub> above 10 µg m<sup>-3</sup> ranged from 7.3 to 27.5, and from 6.2 to 24.6 per 10<sup>5</sup> inhabitants in 2019 and 2020, respectively (Table 2). The number of M-RD for long-term exposure to O<sub>3</sub> in 2019 and 2020 were estimated at 4.7 and 5.4 per 10<sup>5</sup> inhabitants, respectively. The main causes of non-accidental mortality among 10<sup>5</sup> people due to exposure to PM<sub>2.5</sub> was M-COPD for people older than 30-year-old. The rate of mortality due to exposure to PM<sub>2.5</sub> decreased 7.6% per 10<sup>5</sup> inhabitants, while for O<sub>3</sub> an increase of 14.8% M-RD per 10<sup>5</sup> inhabitants was found in 2019 and 2020, respectively. The highest and the lowest annual change in non-accidental deaths for PM<sub>2.5</sub> were observed for M-COPD (+ 1.8 deaths per 10<sup>5</sup> inhabitants) and M-LC (-2.95 deaths per 10<sup>5</sup> inhabitants). Also, M-RD increased (+ 0.7 deaths per 10<sup>5</sup> inhabitants) in 2020 than 2019 due to exposure to different O<sub>3</sub> level. The number of premature deaths in 2020, excluding COVID-19 impact, for PM<sub>2.5</sub> exposure was M-all-cause = 20.4, IHD = 5.4, COPD = 14.4, LC = 6, and for O<sub>3</sub> exposure M-RD = 4.0 per 10<sup>5</sup> inhabitants at risk.

In Ahvaz with a population of about 1.3 million people, M-all-cause and M-RD, respectively for PM<sub>2.5</sub> and O<sub>3</sub> exposure were 240 and 2.72 for adults ≥ 30 year-old (Karimi et al. 2019). In Tehran (Faridi et al. 2018) showed the number of premature M-COPD increased by 57% from 2010 to 2015, while M-IHD was reduced by 28%. With a 10 µg m<sup>-3</sup> increase in the rate of daily PM<sub>2.5</sub> exposure, 1.04% increased mortality for non-accidental causes worldwide (Atkinson et al. 2014). The MED storms is one of the most important reasons which caused high levels of particles in air, and subsequence the increase of mortality

and morbidity in west and southwest of Iran (Khaniabadi et al. 2017d, Khaniabadi et al. 2018b). In Marseille (South of France), the number of non-accidental M-all-cause decreased by 1.15 per 10<sup>5</sup> people approximately (Khaniabadi and Sicard 2021a). The surface O<sub>3</sub> as a global serious problem, has considered in various internal projects in Europe, the United States, and Asia (Sicard et al. 2017). Another study by (Barzeghar et al. 2020) showed M-RD O<sub>3</sub> as SOMO35 increased in Tabriz within 2018 than previous years. The estimated premature M-RD due to exposure to atmospheric O<sub>3</sub> levels in the at-risk population was 143 in 2019 cases while it was 242 in 2013 in Portugal (Brito et al. 2022).

The highest YLL is 1456 in 2019 and then declined by 11.6% in 2020 (Table 3). Results showed exposure to air PM<sub>2.5</sub> in 2019 and 2020 reduced the life expectancy by 0.58 and 0.45 years during each year, respectively. The loss of life expectancy due to PM<sub>2.5</sub> exposure in Iran was estimated at 0.43–1.87 years (Hadei et al. 2020). The YLL attributable to PM<sub>2.5</sub> for individuals higher than 30 year-old was decreased by 30% during 10 years (2006–2015) in Tehran (Faridi et al. 2018).

## 4 Conclusion

In this study, we investigated the temporal trends in PM<sub>2.5</sub> and O<sub>3</sub> concentrations in a southwestern capital city of Iran. The main source of PM<sub>2.5</sub> as most serious health risk within southwest of Iran is MED storms from Arabian countries (Karimi et al. 2019; Goudarzi et al. 2021). This study has conducted with a methodology from high-quality research, but there are still limitations. The interactions between air pollutants and their information are not available, however the health effects are focused on a

**Table 2** At-risk population, estimated AP %, and the number of cases due to long-term exposure to PM<sub>2.5</sub> and O<sub>3</sub> using the 95% CI RR in 2019 and 2020

Health impact	At-risk population		Estimated AP (%)		PM <sub>2.5</sub>		O <sub>3</sub>	
	2019	2020	2019	2020	2019	2020	2019	2020
Mortality, all-cause (age ≥ 30)	134,500	144,200	3.7 (1.3–5.8)	2.8 (2.0–5.1)	27.5 (4.6–37)	24.6 (21–41.2)	–	–
Mortality, IHD (age ≥ 25)	79,800	81,580	5.6 (0.5–11.9)	6.1 (0.8–13.85)	7.3 (6.6–14.9)	6.3(1.2–11.5)	–	–
Mortality, COPD (age ≥ 30)	68,440	71,050	2.7 (0.5–4.9)	1.8 (0.2–2.8)	17.0 (8.9–23.6)	19.2 (5.8–32.6)	–	–
Mortality, LC (age ≥ 30)	54,600	60,750	12.8 (5.9–21.9)	10.4 (3.5–12.85)	9.2 (8.31–11.2)	6.25 (2.45–9.3)	–	–
Mortality, RD (age ≥ 30)	101,560	112,700	13.6 (11.5–15.8)	11.6 (4.7–16.5)	–	–	4.7 (1.56–8.66)	5.4 (1.8–13.42)

**Table 3** Years of life lost and expected life remaining due to exposure to PM<sub>2.5</sub> above 10 µg m<sup>-3</sup> in 2019 and 2020

Year	YLL (age ≥ 30)	YLL for 10 <sup>5</sup> /capita	ELR reduction at age 30
2019	1456 (920–2455)	24.4 (12.87–28.0)	0.58 (0.32–1.08)
2020	1287 (780–1621)	23.0 (17.8–27.5)	0.45 (0.21–0.66)

single pollutant without considering the simultaneous exposure to the multiple pollutants. This study only reflects outdoor exposure while people spend longer indoors (Guan et al. 2021b). A comprehensive estimation of indoor air pollution health effects by (Hu et al. 2020) showed that the indoor exposure accounted for 68% and 34% of that to ambient PM<sub>2.5</sub> and O<sub>3</sub>. Therefore, this study may overestimate the health effects to a certain extent. Our approach assumes that air concentrations measured at the central monitoring point are representative of the exposure of all people living in a city (Khaniabadi et al. 2017b; Guan et al. 2021a). In general, the health effect findings based on daily averaged not suitable for direct comparison (Guan et al. 2021b).

Between 2018 and 2020, PM<sub>2.5</sub> mean concentrations ranged from 27.7 to 41.2 to µg m<sup>-3</sup>, while O<sub>3</sub> levels ranged from 14.2 to 15.7 µg m<sup>-3</sup>. Highest PM<sub>2.5</sub> and O<sub>3</sub> levels were observed during cold and warm seasons with good coefficient correlation in 2019 and 2020. The COVID-19 lockdown reduced PM<sub>2.5</sub> concentrations (–25%) and related mortality (–7.5%) but O<sub>3</sub> levels increased (+ 8%), as well as the O<sub>3</sub>-related number of premature deaths (+ 15%). PM<sub>2.5</sub> concentrations is well correlated to gasoline and natural gas consumption, and negatively correlated to O<sub>3</sub>, leading to a reduction in cost for people (–13.1% and –12.6% respectively in 2020), compared to previous years. In 2019 the number of premature deaths related to PM<sub>2.5</sub> (7.3 to 27.5 per 10<sup>5</sup> people) and O<sub>3</sub> (4.7 per 10<sup>5</sup> people) concentrations changed to 6.3 to 24.6 per 10<sup>5</sup> people and 5.4 per 10<sup>5</sup> people in 2020. Our results showed exposure to PM<sub>2.5</sub> reduced the life expectancy by 0.58 and 0.45 year in 2019 and 2020, respectively. Previous studies provided quantitative estimates of the ability of green infrastructure to ameliorate urban air quality (e.g., PM<sub>2.5</sub>, O<sub>3</sub>) at city scale worldwide (Adhikari and Yin 2020, Khaniabadi and Sicard 2021a).

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## Declarations

**Conflict of interest** Conflict of interest There is no conflict of interest in this study.

## References

- Adhikari A, Yin J (2020) Short-term effects of ambient ozone, PM<sub>2.5</sub>, and meteorological factors on COVID-19 confirmed cases and deaths in queens, new york. *Int J Environ Res Public Health* 17:4047
- Agami S, Dayan U (2021) Impact of the first induced COVID-19 lockdown on air quality in Israel. *Atmos Environ* 262:118627
- Aksoyoglu S, Keller J, Ciarelli G, Prévôt AS, Baltensperger U (2014) A model study on changes of european and swiss particulate matter, ozone and nitrogen deposition between 1990 and 2020 due to the revised gothenburg protocol. *Atmos Chem Phys* 14:13081–13095
- Al-Hemoud A, Gasana J, Alajeel A, Alhamoud E, Al-Shatti A, Al-Khayat A (2020) Ambient exposure of O<sub>3</sub> and NO<sub>2</sub> and associated health risk in Kuwait. *Environ Sci Pollut Res* 28:1–10
- Amann M, Purohit P, Bhanarkar AD, Bertok I, Borcken-Kleefeld J, Cofala J, Heyes C, Kiesewetter G, Klimont Z, Liu J (2017) Managing future air quality in megacities: a case study for delhi. *Atmos Environ* 161:99–111
- Amoatey P, Takdastan A, Sicard P, Hopke PK, Baawain M, Omidvarborna H, Allahyari S, Esmailzadeh A, De Marco A, Khaniabadi YO (2019) Short and long-term impacts of ambient ozone on health in ahvaz Iran. *Human Ecol Risk Assess Int J* 25:1336
- Amoatey P, Sicard P, De Marco A, Khaniabadi YO (2020) Long-term exposure to ambient PM<sub>2.5</sub> and impacts on health in rome Italy. *Clin Epidemiol Glob Health* 8:531–535
- Amoatey P, Khaniabadi YO, Sicard P, Siddiqi SA, De Marco A, Sulaiman H (2021) Temporal incidence and prevalence of bronchitis and morbidities from exposure to ambient PM<sub>2.5</sub> and PM<sub>10</sub>. *Environ Justice* 14:267–276
- Anderson HR (2009) Air pollution and mortality: a history. *Atmos Environ* 43:142–152
- Atkinson R, Kang S, Anderson H, Mills I, Walton H (2014) Epidemiological time series studies of PM<sub>2.5</sub> and daily mortality and hospital admissions: a systematic review and meta-analysis. *Thorax* 69:660–665
- Barzeghar V, Sarbakhsh P, Hassanvand MS, Faridi S, Gholampour A (2020) Long-term trend of ambient air PM<sub>10</sub>, PM<sub>2.5</sub>, and O<sub>3</sub> and their health effects in tabriz city, Iran, during 2006–2017. *Sustain Cities Soc* 54:101988
- Bhatti UA, Zeeshan Z, Nizamani MM, Bazai S, Yu Z, Yuan L (2021) Assessing the change of ambient air quality patterns in jiangsu province of china pre-to post-COVID-19. *Chemosphere* 288:132569
- Bogaert P, Christakos G, Jerrett M, Yu H-L (2009) Spatiotemporal modelling of ozone distribution in the state of california. *Atmos Environ* 43:2471–2480
- Bressi M, Sciare J, Ghersi V, Bonnaire N, Nicolas J, Petit J-E, Moukhtar S, Rosso A, Mihalopoulos N, Féron A (2013) A one-year comprehensive chemical characterisation of fine aerosol (PM<sub>2.5</sub>) at urban, suburban and rural background sites in the region of Paris (France). *Atmos Chem Phys* 13:7825–7844
- Brito J, Bernardo A, Gonçalves LL (2022) Atmospheric pollution and mortality in portugal: quantitative assessment of the environmental burden of disease using the AirQ+ model. *Sci Total Environ* 285:152964



- Broomandi P, Crape B, Jahanbakhshi A, Janatian N, Nikfal A, Tamjidi M, Kim JR, Middleton N, Karaca F (2022) Assessment of the association between dust storms and COVID-19 infection rate in southwest Iran. *Environ Sci Pollut Res* 29:1–20
- Burnett RT, Pope CA III, Ezzati M, Olives C, Lim SS, Mehta S, Shin HH, 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
- Christakos G, Kolovos A (1999) A study of the spatiotemporal health impacts of ozone exposure. *J Exposure Sci Environ Epidemiol* 9:322–335
- Crouse DL, Peters PA, Hystad P, Brook JR, van Donkelaar A, Martin RV, Villeneuve PJ, Jerrett M, Goldberg MS, Pope CA III (2015) Ambient PM<sub>2.5</sub>, O<sub>3</sub>, and NO<sub>2</sub> exposures and associations with mortality over 16 years of follow-up in the Canadian census health and environment cohort (CanCHEC). *Environ Health Perspect* 123:1180–1186
- Daryanoosh M, Goudarzi G, Rashidi R, Keishams F, Hopke PK, Mohammadi MJ, Nourmoradi H, Sicard P, Takdastan A, Vosoughi M, Veysi M, Kianizadeh M, Khaniabadi YO (2017) Risk of morbidity attributed to ambient PM<sub>10</sub> in the western cities of Iran. *Toxin Rev*. <https://doi.org/10.1080/15569543.15562017.11370602>
- Daryanoosh M, Goudarzi G, Rashidi R, Keishams F, Hopke PK, Mohammadi MJ, Nourmoradi H, Sicard P, Takdastan A, Vosoughi M (2018) Risk of morbidity attributed to ambient PM<sub>10</sub> in the western cities of Iran. *Toxin Rev* 37:313–318
- De Marco A, Amoatey P, Khaniabadi YO, Sicard P, Hopke PK (2018) Mortality and morbidity for cardiopulmonary diseases attributed to PM<sub>2.5</sub> exposure in the metropolis of Rome Italy. *Eur J Intern Med* 57:49–57
- De Marco A, Garcia-Gomez H, Collalti A, Khaniabadi YO, Feng Z, Proietti C, Sicard P, Vitale M, Anav A, Paoletti E (2022) Ozone modelling and mapping for risk assessment: an overview of different approaches for human and ecosystems health. *Environ Res* 211:113048
- De Marco A, Sicard P, Feng Z, Agathokleous E, Alonso R, Araminiene V, Augustaitis A, Badea O, Beasley JC, Branquinho C (2022) Strategic roadmap to assess forest vulnerability under air pollution and climate change. *Glob Ch Biol*. <https://doi.org/10.1111/gcb.16278>
- Faridi S, Shamsipour M, Krzyzanowski M, Künzli N, Amini H, Azimi F, Malkawi M, Momeniha F, Gholampour A, Hassanvand MS (2018) Long-term trends and health impact of PM<sub>2.5</sub> and O<sub>3</sub> in Tehran, Iran, 2006–2015. *Environ Int* 114:37–49
- Farzadfar F, Naghavi M, Sepanlou SG, Moghaddam SS, Dangel WJ, Weaver ND, Aminoroaya A, Azadnajafabad S, Koolaji S, Mohammadi E (2022) Health system performance in Iran: a systematic analysis for the global burden of disease study 2019. *Lancet* 399:1625–1645
- Fattore E, Paiano V, Borgini A, Tittarelli A, Bertoldi M, Crosignani P, Fanelli R (2011) Human health risk in relation to air quality in two municipalities in an industrialized area of northern Italy. *Environ Res* 111:1321–1327
- Garrett P, Casimiro E (2011) Short-term effect of fine particulate matter (PM<sub>2.5</sub>) and ozone on daily mortality in Lisbon. *Port Environ Sci Pollut Res* 18:1585–1592
- Goodman JE, Prueitt RL, Sax SN, Pizzurro DM, Lynch HN, Zu K, Venditti FJ (2015) Ozone exposure and systemic biomarkers: evaluation of evidence for adverse cardiovascular health impacts. *Crit Rev Toxicol* 45:412–452
- Goudarzi G, Hopke PK, Yazdani M (2021) Forecasting PM<sub>2.5</sub> concentration using artificial neural network and its health effects in Ahvaz Iran. *Chemosphere* 283:131285
- Guan W-J, Zheng X-Y, Chung KF, Zhong N-S (2016) Impact of air pollution on the burden of chronic respiratory diseases in China: time for urgent action. *Lancet* 388:1939–1951
- Guan Y, Xiao Y, Rong B, Zhang N, Chu C (2021) Long-term health impacts attributable to PM<sub>2.5</sub> and ozone pollution in China's most polluted region during 2015–2020. *J Clean Prod* 321:128970
- Guan Y, Xiao Y, Wang Y, Zhang N, Chu C (2021) Assessing the health impacts attributable to PM<sub>2.5</sub> and ozone pollution in 338 Chinese cities from 2015 to 2020. *Environ Pollut* 287:117623
- Güngör BO, Ertuğrul HM, Soytaş U (2021) Impact of COVID-19 outbreak on Turkish gasoline consumption. *Technol Forecast Soc Chang* 166:120637
- Guo H, Ling Z, Cheng H, Simpson I, Lyu X, Wang X, Shao M, Lu H, Ayoko G, Zhang Y (2017) Tropospheric volatile organic compounds in China. *Sci Total Environ* 574:1021–1043
- Gurjar B, Jain A, Sharma A, Agarwal A, Gupta P, Nagpure A, Lelieveld J (2010) Human health risks in megacities due to air pollution. *Atmos Environ* 44:4606–4613
- Hadei M, Nazari SSH, Eslami A, Khosravi A, Yarahmadi M, Naghdali Z, Shahsavani A (2017) Distribution and number of ischemic heart disease (IHD) and stroke deaths due to chronic exposure to PM<sub>2.5</sub> in 10 cities of Iran (2013–2015); an AirQ+ modelling. *J Air Pollut Health* 2:129–136
- Hadei M, Shahsavani A, Krzyzanowski M, Querol X, Stafoggia M, Nazari SSH, Jafari AJ, Yarahmadi M, Kermani M, Khosravi A (2020) Burden of mortality attributed to PM<sub>2.5</sub> exposure in cities of Iran; contribution of short-term pollution peaks. *Atmos Environ* 224:117365
- Hasheminassab S, Daher N, Ostro BD, Sioutas C (2014) Long-term source apportionment of ambient fine particulate matter (PM<sub>2.5</sub>) in the Los Angeles basin: a focus on emissions reduction from vehicular sources. *Environ Pollut* 193:54–64
- Hashemzadeh B, Idani E, Goudarzi G, Ankali KA, Sakhvidi MJZ, Babaei AA, Hashemzadeh H, Vosoughi M, Mohammadi MJ, Neisi A (2019) Effects of PM<sub>2.5</sub> and NO<sub>2</sub> on the 8-isoprostane and lung function indices of FVC and FEV1 in students of Ahvaz city Iran. *Saudi J Biol Sci* 26:473–480
- Héroux M-E, Anderson HR, Atkinson R, Brunekreef B, Cohen A, Forastiere F, Hurley F, Katsouyanni K, Krewski D, Krzyzanowski M (2015) Quantifying the health impacts of ambient air pollutants: recommendations of a WHO/Europe project. *Int J Public Health* 60:619–627
- Hu Y, Yao M, Liu Y, Zhao B (2020) Personal exposure to ambient PM<sub>2.5</sub>, PM<sub>10</sub>, O<sub>3</sub>, NO<sub>2</sub>, and SO<sub>2</sub> for different populations in 31 Chinese provinces. *Environ Int* 144:106018
- Karimi A, Shirmardi M, Hadeie M, Birgani YT, Neisi A, Takdastan A, Goudarzi G (2019) Concentrations and health effects of short- and long-term exposure to PM<sub>2.5</sub>, NO<sub>2</sub>, and O<sub>3</sub> in ambient air of Ahvaz city, Iran (2014–2017). *Ecotoxicology and Environmental Safety* 180: 542–548
- Kerimray A, Baimatova N, Ibragimova OP, Bukenov B, Kenessov B, Plotitsyn P, Karaca F (2020) Assessing air quality changes in large cities during COVID-19 lockdowns: the impacts of traffic-free urban conditions in Almaty. *Kaz Sci Total Environ* 730:139179
- Khaniabadi YO, Sicard P (2021) A 10-year assessment of ambient fine particles and related health endpoints in a large Mediterranean city. *Chemosphere* 278:130502
- Khaniabadi YO, Goudarzi G, Daryanoosh SM, Borgini A, Tittarelli A, De Marco A (2017a) Exposure to PM<sub>10</sub>, NO<sub>2</sub>, and O<sub>3</sub> and impacts on human health. *Environ Sci Pollut Res* 24:2781–2789
- Khaniabadi YO, Hopke PK, Goudarzi G, Daryanoosh SM, Jourvand M, Basiri H (2017b) Cardiopulmonary mortality and COPD attributed to ambient ozone. *Environ Res* 152:336–341
- Khaniabadi YO, Daryanoosh SM, Amrane A, Polosa R, Hopke PK, Goudarzi G, Mohammadi MJ, Sicard P, Armin H (2017c) Impact

- of middle eastern dust storms on human health. *Atmos Pollut Res* 8:606–613
- Khaniabadi YO, Fanelli R, De Marco A, Daryanoosh SM, Kloog I, Hopke PK, Conti GO, Ferrante M, Mohammadi MJ, Babaei AA (2017d) Hospital admissions in Iran for cardiovascular and respiratory diseases attributed to the middle eastern dust storms. *Environ Sci Pollut Res* 24:16860–16868
- Khaniabadi YO, Daryanoosh M, Sicard P, Takdastan A, Hopke PK, Esmaeili S, De Marco A, Rashidi R (2018) Chronic obstructive pulmonary diseases related to outdoor PM<sub>10</sub>, O<sub>3</sub>, SO<sub>2</sub>, and NO<sub>2</sub> in a heavily polluted megacity of Iran. *Environ Sci Pollut Res* 25:17726–17734
- Khaniabadi YO, Sicard P, Takdastan A, Hopke PK, Taiwo AM, Khaniabadi FO, De Marco A, Daryanoosh M (2019) Mortality and morbidity due to ambient air pollution in Iran. *Clin Epidemiol Glob Health* 7:222–227
- Kheirbek I, Wheeler K, Walters S, Kass D, Matte T (2013) PM<sub>2.5</sub> and ozone health impacts and disparities in new york city: sensitivity to spatial and temporal resolution. *Air Qual Atmos Health* 6:473–486
- Khomenko S, Cirach M, Pereira-Barboza E, Mueller N, Barrera-Gómez J, Rojas-Rueda D, de Hoogh K, Hoek G, Nieuwenhuijsen M (2021) Premature mortality due to air pollution in European cities: a health impact assessment. *Lancet Planet Health* 5:e121–e134
- Landrigan PJ, Fuller R, Acosta NJ, Adeyi O, Arnold R, Baldé AB, Bertollini R, Bose-O'Reilly S, Boufford JI, Breysse PN (2018) The lancet commission on pollution and health. *Lancet* 391:462–512
- Li M, Wang T, Xie M, Zhuang B, Li S, Han Y, Chen P (2017) Impacts of aerosol-radiation feedback on local air quality during a severe haze episode in nanjing megacity, eastern china. *Tellus B Chem Phys Meteorol* 69:1339548
- Liu Y, Pan J, Fan C, Xu R, Wang Y, Xu C, Xie S, Zhang H, Cui X, Peng Z (2021) Short-term exposure to ambient air pollution and mortality from myocardial infarction. *J Am Coll Cardiol* 77:271–281
- Mannucci PM (2022) Cardiovascular health and ambient air pollution: lower is not enough. *Eur J Prev Cardiol* 29:1200–1201
- Naghan DJ, Neisi A, Goudarzi G, Dastoorpoor M, Fadaei A, Angali KA (2022) Estimation of the effects PM<sub>2.5</sub>, NO<sub>2</sub>, O<sub>3</sub> pollutants on the health of shahrekord residents based on AirQ+ software during (2012–2018). *Toxicol Rep* 9:842
- Neira MP (2019) Air pollution and human health: a comment from the World Health Organization. *Ann Glob Health*. <https://doi.org/10.5334/aogh.2712>
- Neisi A, Vosoughi M, Shirmardi M, Idani E, Goudarzi G, Hazrati S, Mohammadi MJ, Asadi A, Asgharnia H, Hashemzadeh B (2018) Concentration of air pollutants as toxic matter in urban and rural areas of Ahvaz. *Toxin Rev* 37:243–250
- O'Donovan MR, Gapp C, Stein C (2018) Burden of disease studies in the WHO european region—a mapping exercise. *Eur J Pub Health* 28:773–778
- Omidic Khaniabadi Y, Sicard P, Omidic Khaniabadi A, Mohammadinejad S, Keishams F, Takdastan A, Najafi A, De Marco A, Daryanoosh M (2019) Air quality modeling for health risk assessment of ambient PM<sub>10</sub>, PM<sub>2.5</sub> and SO<sub>2</sub> in Iran. *Hum Ecol Risk Assess Int J* 25:1298–1310
- Ostro B, Spadaro JV, Gumy S, Mudu P, Awe Y, Forastiere F, Peters A (2018) Assessing the recent estimates of the global burden of disease for ambient air pollution: methodological changes and implications for low-and middle-income countries. *Environ Res* 166:713–725
- Rovira J, Domingo JL, Schuhmacher M (2020) Air quality, health impacts and burden of disease due to air pollution (PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub> and O<sub>3</sub>): Application of AirQ+ model to the Camp de Tarragona County (Catalonia, Spain). *Sci Total Environ* 703:135538
- Shin HH, Gogna P, Maquiling A, Parajuli RP, Haque L, Burr B (2021) Comparison of hospitalization and mortality associated with short-term exposure to ambient ozone and PM<sub>2.5</sub> in canada. *Chemosphere* 265:128683
- Sicard P (2021) Ground-level ozone over time: an observation-based global overview. *Curr Opin Environ Sci Health* 19:100226
- Sicard P, Khaniabadi YO, Perez S, Gualtieri M, De Marco A (2019) Effect of O<sub>3</sub>, PM<sub>10</sub> and PM<sub>2.5</sub> on cardiovascular and respiratory diseases in cities of France, Iran and Italy. *Environ Sci Pollut Res* 26:32645–32665
- Sicard P, De Marco A, Agathokleous E, Feng Z, Xu X, Paoletti E, Rodriguez JJD, Calatayud V (2020) Amplified ozone pollution in cities during the COVID-19 lockdown. *Sci Total Environ* 735:139542
- Siciliano B, Dantas G, da Silva CM, Arbilla G (2020) Increased ozone levels during the COVID-19 lockdown: analysis for the city of Rio de Janeiro. *Braz Sci Total Environ* 737:139765
- Tian X, An C, Chen Z, Tian Z (2021) Assessing the impact of COVID-19 pandemic on urban transportation and air quality in canada. *Sci Total Environ* 765:144270
- Toe S, Nagy M, Albar Z, Nazzinda R, Sattar A, Musiime V, Etajak S, Walyawula F, McComsey GA, Atuyambe L (2021) Ambient air pollution and cardiovascular disease in Ugandan adolescents with perinatally acquired HIV: a cross-sectional study. *Lancet Glob Health* 9:S21
- Wang Y, Wild O, Chen X, Wu Q, Gao M, Chen H, Qi Y, Wang Z (2020) Health impacts of long-term ozone exposure in china over 2013–2017. *Environ Int* 144:106030
- Wu R, Xie S (2017) Spatial distribution of ozone formation in china derived from emissions of speciated volatile organic compounds. *Environ Sci Technol* 51:2574–2583
- Xie Y, Dai H, Zhang Y, Wu Y, Hanaoka T, Masui T (2019) Comparison of health and economic impacts of PM<sub>2.5</sub> and ozone pollution in china. *Environ Int* 130:104881
- Yazdi MD, Wang Y, Di Q, Zanobetti A, Schwartz J (2019) Long-term exposure to PM<sub>2.5</sub> and ozone and hospital admissions of medicare participants in the southeast USA. *Environ Int* 130:104879
- Zhang W, Li W, An X, Zhao Y, Sheng L, Hai S, Li X, Wang F, Zi Z, Chu M (2022) Numerical study of the amplification effects of cold-front passage on air pollution over the north china plain. *Sci Total Environ* 833:155231
- Zhao S, Liu S, Hou X, Sun Y, Beazley R (2021) Air pollution and cause-specific mortality: a comparative study of urban and rural areas in china. *Chemosphere* 262:127884
- Zoran MA, Savastru RS, Savastru DM, Tautan MN (2020) Assessing the relationship between ground levels of ozone (O<sub>3</sub>) and nitrogen dioxide (NO<sub>2</sub>) with coronavirus (COVID-19) in milan Italy. *Sci Total Environ* 740:140005

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