



Ambient PM_{2.5} and O₃ 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_{2.5}) and tropospheric ozone (O₃) time series in Khorramabad (Iran) between 2019 (before) and 2020 (during COVID-19 pandemic); (ii) assess relationship between PM_{2.5} and O₃, the PM_{2.5}/O₃ ratio, and energy consumption; and (iii) estimate the health effects of exposure to ambient PM_{2.5} and O₃. From hourly PM_{2.5} and O₃ 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_{2.5} and O₃ ($r = -0.46$ 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_{2.5} exposure and for respiratory diseases (4.7 and 5.4) for exposure to O₃ above 10 µg m⁻³ 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_{2.5} 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_{2.5} (–25.5%) and an increase of O₃ concentration (+ 8.0%) in Khorramabad.

Keywords Air pollution · Health effect · PM_{2.5} · O₃ · 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 ₃ 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_{2.5} and PM₁₀), tropospheric ozone (O₃) and nitrogen dioxide (NO₂) 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_{2.5},

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PM₁₀, O₃ and NO₂) 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_{2.5} and O₃ 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_{2.5} 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 O₃ 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_{2.5} and O₃ 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_{2.5} and O₃ 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_{2.5} and O₃. The main objectives of the present study were to investigate the health effects of PM_{2.5} and O₃ 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).

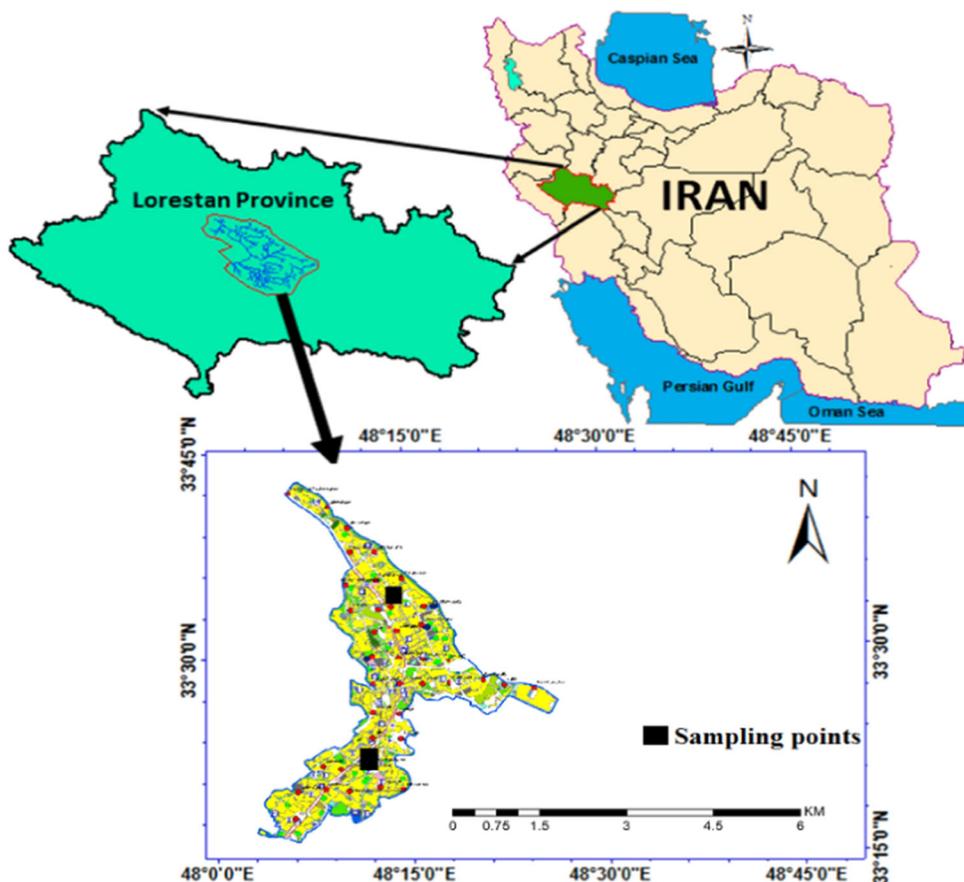
2.2 Data collection

The hourly PM_{2.5} and O₃ 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 ± 3 . The PM_{2.5}/O₃ ratio was calculated to fully understand the relationship between PM_{2.5} and O₃. 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 β 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 α , γ and δ 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).

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

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 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_{valid}) according to below equation (Eq. 5).

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

where, N_{total} = total number of days in a calendar year (365 days in 2019, 366 in 2020), N_{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 β 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).

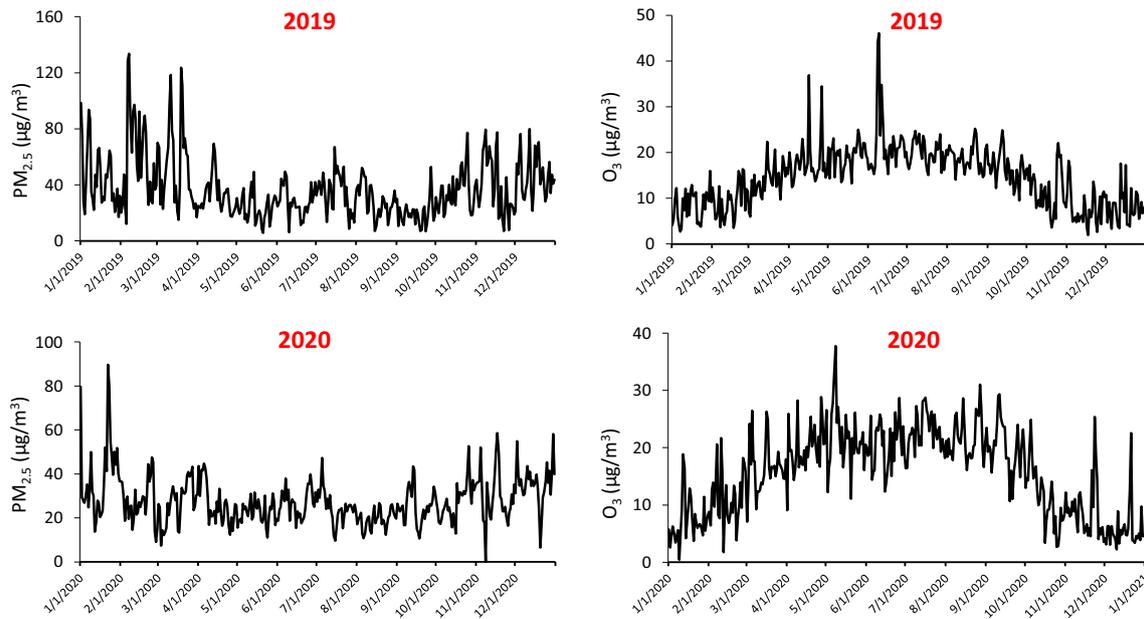
3.2 Relationship between $PM_{2.5}$ and O_3

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_{2.5} and O₃ concentrations (lag0-1 days) more than 10 µg m⁻³

Health outcomes	BI	RR per 10 µg m ⁻³ (95% CI)	Ref
PM_{2.5}			
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)
O₃			
Mortality, respiratory diseases (age ≥ 30)	44–53	1.014 (1.005–1.024)	Héroux et al. (2015)

**Fig. 2** Time series trends of PM_{2.5} and O₃ 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_{2.5} concentrations and to higher O₃ 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_{2.5} and O₃ 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_{2.5} by—25.5%. Furthermore, the annual averages O₃ in 2020 compared to previous years increased by + 8.0% during COVID-19 year.

(Sicard et al. 2020) showed that O₃ increased in Wuhan, Valencia, Nice and Rome higher than previous years 2017–2019, while PM_{2.5} 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_{2.5} concentrations compared to the time period 2010–2019 (Khaniabadi and Sicard 2021b). Another study showed that O₃ 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_{2.5} during 2019 and 2020 were respectively 40 and 31 µg m⁻³, 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)

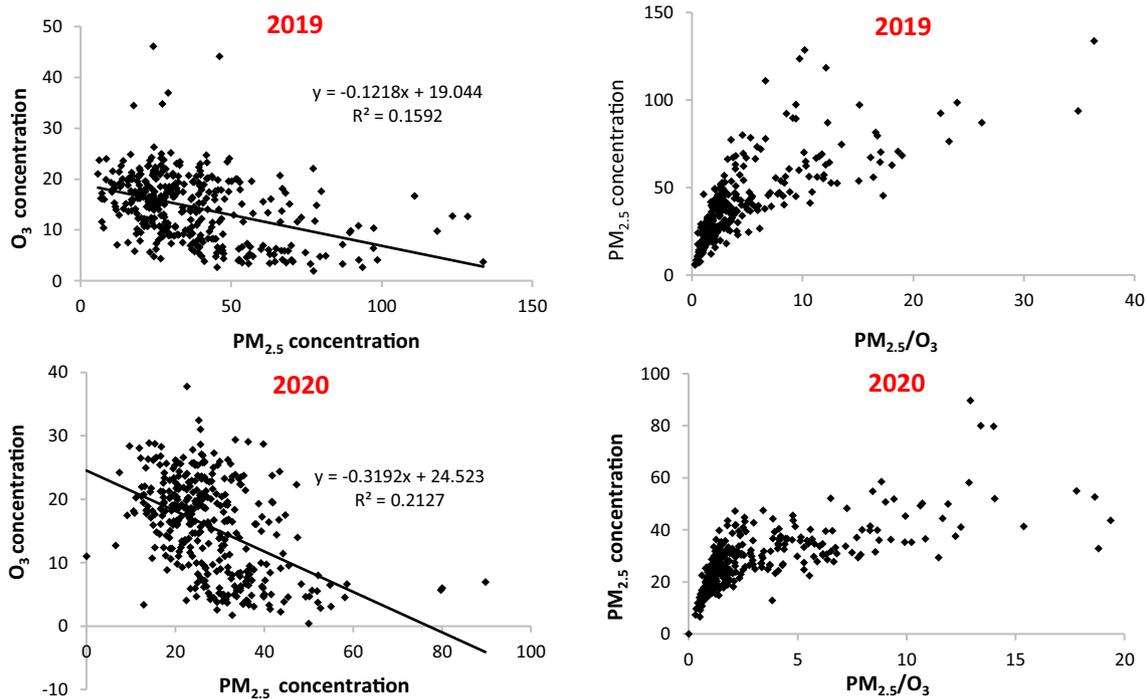


Fig.3 (left) Correlation between PM_{2.5} with O₃ levels, and (right) relationship between PM_{2.5}/O₃ ratio with PM_{2.5} during 2019 and 2020 across Khorramabad, Iran

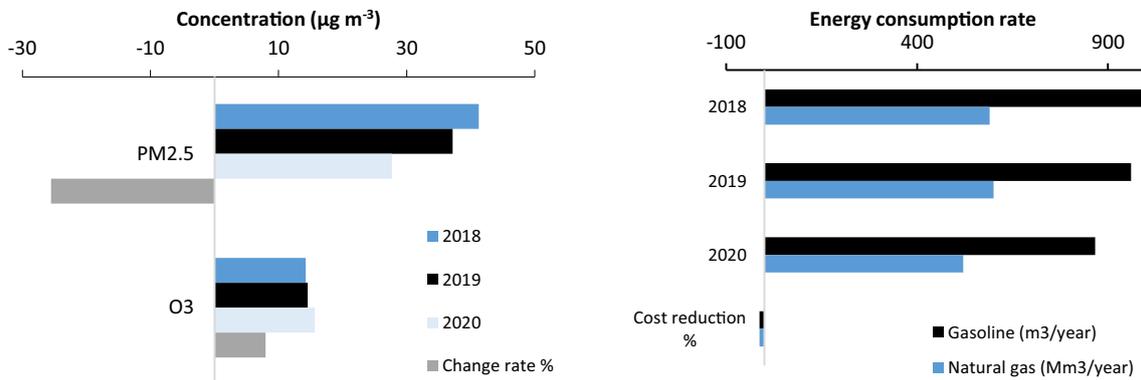


Fig.4 (left) Comparative bar between PM_{2.5} and O₃ averages in 2018, 2019 (before COVID-19) with 2020 (during COVID-19), and (right) Cost reduction in fuel consumption in 2018, 2019 (before COVID-19) with 2020 (during COVID-19) across Khorramabad, Iran

and during-COVID-19 (2020) showed a lowering in the cost of consumption fuels during the COVID-19. The variation rate for gasoline ($\text{m}^3 \text{ year}^{-1}$) and natural gas (in $\text{Mm}^3 \text{ year}^{-1}$) 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 O₃ 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_{2.5} and O₃ and the years of life lost

The number of premature deaths for non-accidental causes for PM_{2.5} above 10 µg m⁻³ ranged from 7.3 to 27.5, and from 6.2 to 24.6 per 10⁵ inhabitants in 2019 and 2020, respectively (Table 2). The number of M-RD for long-term exposure to O₃ in 2019 and 2020 were estimated at 4.7 and 5.4 per 10⁵ inhabitants, respectively. The main causes of non-accidental mortality among 10⁵ people due to exposure to PM_{2.5} was M-COPD for people older than 30-year-old. The rate of mortality due to exposure to PM_{2.5} decreased 7.6% per 10⁵ inhabitants, while for O₃ an increase of 14.8% M-RD per 10⁵ inhabitants was found in 2019 and 2020, respectively. The highest and the lowest annual change in non-accidental deaths for PM_{2.5} were observed for M-COPD (+ 1.8 deaths per 10⁵ inhabitants) and M-LC (-2.95 deaths per 10⁵ inhabitants). Also, M-RD increased (+ 0.7 deaths per 10⁵ inhabitants) in 2020 than 2019 due to exposure to different O₃ level. The number of premature deaths in 2020, excluding COVID-19 impact, for PM_{2.5} exposure was M-all-cause = 20.4, IHD = 5.4, COPD = 14.4, LC = 6, and for O₃ exposure M-RD = 4.0 per 10⁵ inhabitants at risk.

In Ahvaz with a population of about 1.3 million people, M-all-cause and M-RD, respectively for PM_{2.5} and O₃ 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⁻³ increase in the rate of daily PM_{2.5} 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 10⁵ people approximately (Khaniabadi and Sicard 2021a). The surface O₃ 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 O₃ as SOMO35 increased in Tabriz within 2018 than previous years. The estimated premature M-RD due to exposure to atmospheric O₃ 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_{2.5} 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_{2.5} exposure in Iran was estimated at 0.43–1.87 years (Hadei et al. 2020). The YLL attributable to PM_{2.5} 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_{2.5} and O₃ concentrations in a southwestern capital city of Iran. The main source of PM_{2.5} 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_{2.5} and O₃ using the 95% CI RR in 2019 and 2020

Health impact	At-risk population		Estimated AP (%)		PM _{2.5}		O ₃	
	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_{2.5} above 10 µg m⁻³ in 2019 and 2020

Year	YLL (age ≥ 30)	YLL for 10 ⁵ /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_{2.5} and O₃. 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_{2.5} mean concentrations ranged from 27.7 to 41.2 to µg m⁻³, while O₃ levels ranged from 14.2 to 15.7 µg m⁻³. Highest PM_{2.5} and O₃ levels were observed during cold and warm seasons with good coefficient correlation in 2019 and 2020. The COVID-19 lockdown reduced PM_{2.5} concentrations (–25%) and related mortality (–7.5%) but O₃ levels increased (+ 8%), as well as the O₃-related number of premature deaths (+ 15%). PM_{2.5} concentrations is well correlated to gasoline and natural gas consumption, and negatively correlated to O₃, 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_{2.5} (7.3 to 27.5 per 10⁵ people) and O₃ (4.7 per 10⁵ people) concentrations changed to 6.3 to 24.6 per 10⁵ people and 5.4 per 10⁵ people in 2020. Our results showed exposure to PM_{2.5} 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_{2.5}, O₃) 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.

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