

Original Research

Integrated Risk Assessment of Multiple Air Pollutants and Influence Factors in an Urban Agglomeration of China

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Abstract

There has been an increasing interest in evaluating health effects associated with multiple air pollutants. Identifying the critical factors driving the variation of multiple air pollutants and pollution caused the human health risk are still limited. We selected four typical cities as the study object in the Central Plains Urban Agglomeration (CPUA), China and collected the data of air pollutants, meteorological factors and social development factors over the two years. Our results showed that the air pollutants presented remarkable seasonal variations, according to the principal coordinate analysis (PCoA), the air pollution event often occurred in winter in the CPUA, and the air quality health index (AQHI) values were moderate risk for population health particularly in Zhengzhou and Anyang. The results of the correlation analysis and redundancy analysis (RDA) showed that air pollution and associated health risk was driven by human activities, and was influenced by dominant meteorological factors, such as, rainfall, vapor pressure, relative humidity. These indicated that the air pollution in the CPUA should make the pollutant emission plan according to the region and season to improve the air quality and protect the public health.

Keywords: air pollution, health risk, Air Quality Health Index, urban agglomeration

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Introduction

The effects of rapid urbanization and developing urban agglomerations on environmental pollution had been verified by many studies [1-3]. The influences of air pollution on human health and ecosystem are widely concerned on the field of environmental protection. As officially reported, China's urbanization rate increased from 10.64% in 1949 to 59.58% in 2018, which was driven by large-scale demographic migration and social and economic development. Urbanization not only drives social development, human civilization and technological invention, but also accelerate the population density and the energy and resource consumption, and causes the environment problem [4-6]. For example, current study found that a 0.167% increase in $PM_{2.5}$ concentrations, for every 1% increase in population density in the Yangtze river delta (YRD) region [7]. On a worldwide basis, 91% populations are exposed to undesirable air quality, which were closely related to both chronic and acute cardiovascular and respiratory diseases, even death [8].

Atmospheric pollutants, such as particulate matter ($PM_{2.5}$ and PM_{10}), [9], nitrogen dioxide (NO_2) [10], ozone (O_3) [11], carbon monoxide (CO) and sulfur dioxide (SO_2) [12, 11], have drawn great public attention, due to be associated with a wide range of effects on human health [13]. Epidemiological studies have shown that $PM_{2.5}$ can attach the pollutants and enter human respiratory system, even penetrate through lung cells into the blood circulation [14], it brings harms to human health. Similarly, gaseous pollutants in the air can also affect the physical activity and pathological state of the body [13]. In most cases, people are exposed to multiple pollutants in daily life. Meanwhile, the atmosphere is a complex dynamic system with multiple pollutants interactions. It is difficult to explain the influence mechanism of cooperation of multiple pollutants on human health [15]. Therefore, many studies recommended aggregate risk index instead of single pollutant risk [16, 17]. The Air Quality Index (AQI) and Air Pollution Index (API) has been widely used to assess the quality of ambient air [18, 19], which used to aim to meet the management rather than reflect the direct relations between pollutants and health risk [20, 21]. A new multipollutant air quality health index (AQHI) was proposed in Canada, which was based on the total of excess mortality risk associated with individual pollutants from a time-series analysis. [21] At present, the

evaluation system of AQHI has been established in some cities in China, such as, Lanzhou [22], Shanghai [20], Guangzhou [23], and Hong Kong [24]. These results show that the AQHI can help understand the sum of short term health risk of air pollution mixture. Thereafter, it is necessary to establish the nationwide evaluation system based on the AQHI, of course, more research is needed to improve this system.

The variations of air pollutants are often influenced by various environmental and anthropogenic factors [25]. Therefore, the human health risks initiated by pollutants are also affected by these factors, such as hydro-meteorological factors, topographical factor and economic and social indicators. The current study from western China reported that spatiotemporal changes of pollutants were correlated with the residential emissions, indicating that the reduction of anthropogenic emissions was needed to improve the local air quality [26]. However, the results showed that the influence of factors on air pollutants emissions vary by region [27]. Air pollutants as risk factors for respiratory diseases of children and adults were verified by numerous work [8]. In addition, the health effects estimates might be different from age, seasonal changes and regional development [7]. The variations of different air pollutant vary in stages and regional scale, such as, the fluctuation of O_3 variation curve is very different from other air pollutants. Thus, the interaction among air pollutants, influence factors and health risk can also be seen as a complex dynamic process. Previous studies paid much attention to the effect of environmental factors on a single pollutant, which could not accurately reflect actual circumstances [28, 29]. In addition, many studies did not take into account the effect of anthropogenic source, namely, emission source [30], which have adverse effects on making the strategies of air pollution control.

The Central Plains Urban Agglomeration (CPUA) has the highest rate of urbanization and highest population density in China, and the development planning of the region has been upgraded to a national strategy. In this paper, four typical cities in the CPUA were selected to investigate the influence of environmental and anthropogenic factors on the dynamic change of multiple air pollutants and associated health risk. Specifically, the main objectives of this study are to: (1) describe the spatiotemporal characteristics of six pollutants in the ambient air of CPUA; (2) investigate the dominant factors influencing the

pollutants and health risk; (3) illustrate the variation mechanisms of pollutants and the health risk at a regional scale. Also note that the multivariate statistical analysis was employed to achieve the goal mentioned above. The results can enhance the understanding of the critical factors driving the occurrence of air pollution events and the risk of adverse health conditions, which also assist policymakers set priorities and make the control strategy for the regional air quality management.

Methods and Materials

Study Area

As shown in Fig. 1, the CPUA region is located in central and eastern part of China, including 30 cities in five provinces, which covers roughly 287,000 km² with the population of 163.53 million, and of these, 14 cities are located in the core area of the CPUA. The region is becoming China's important economic growth pole, due to the convenient multimodal transportation, improved logistics network and developed manufacturing industry. According to the previous work, the typical cities in the CPUA region, such as Zhengzhou, Xinxiang and Anyang in Henan province, had suffered serious air pollution due to the complex interaction between intensive pollutants emissions and unfavorable meteorological conditions [31, 32]. The region is subject to a temperate continental monsoon. The annual average temperature is 12.7°C–16.2°C, with an annual average

humidity of 60%–80%, and the sunshine duration is 1468–2247 h, the average frost-free period 208–272 d. The average annual precipitation ranges from 477.8 to 1167.3 mm, 50% of the annual precipitation concentrated mostly in Summer (June to August).

Data Sources

The monthly data of AQI and air pollutants including PM_{2.5}, PM₁₀, SO₂, CO, NO₂ and O₃ were collected in the China National Environmental Monitoring Center, from September 2017 to August 2019. In this study, the influence factors including the meteorological factors and social economic indicators, which represent the environmental and anthropogenic factors, respectively. The meteorological data at the monitoring sites, including rainfall amount, precipitation days (> 0.1 mm), air temperature, atmosphere and vapor pressure, relative humidity, wind speed, and sunshine duration were provided by the China Data Centre for Meteorology. The industrial electricity and total social electricity consumption data were obtained from the monthly economic report of the local the official website of government. The data sources statistic results of these data are introduced in detail in the supporting information.

Assessment Method

The AQI has replaced the API to assess the air quality in 2012 in China. The AQI measures the overall quality of the air, which can meet



Fig. 1. Location of the Central Plain Urban Agglomeration (CPUA) region of China.

the air quality management goal. Although the AQI have been used successfully in various country, it could neither present the effect of multiple air pollutants on the health risk nor reflect the relationships between the two (Stieb, et al., 2008; Chen, et al., 2013). In order to fill the gap of the AQI, the AQHI methods had been developed based on the relation between mortality and associated health risk [21]. Generally, the AQHI can reflect the health effects of air pollution from the perspective of the epidemiology in the general population and directly provide the information about the health risks for the public [13]. The calculation of AQHI is shown in Eq. (1):

$$AQHI = (10/c) \sum_{i=1 \dots n} 100[\exp(\beta_i x_i) - 1] \quad (1)$$

...where β_i is the coefficient of Poisson regression model, x_i is the concentration of the pollutant i . The c is the scaling factor, and the value is 16.4% [20]. Due to the AQHI is an unbounded index, on a 0-10+ scale, which has four bands, including “Low (0-3), Moderate (4-6), High (6-9) and Very High (>10) risk” of increase [17, 21]. In this study, the AQHI was determined using the derived model based on the data of “The China Air Pollution and Health Effects Study” [13, 20]:

$$AQHI = (10/16.4) \times 100 \times [\exp(0.00019 \times PM_{10}) - 1 + \exp(0.00061 \times NO_2) - 1] \quad (2)$$

Statistical Analysis

The normality test of data was determined by the non-parametric Kolmogorov-Smirnov ($K-S$) test, and non-normal data were processed using log10 transformation [5, 33]. One-way ANOVA was used to identify differences among groups of variables using a Tukey’s post hoc with a significance <0.05 [5]. The principal coordinate analysis (PCoA) by the Bray-curtis distance metric was adopted to identify association among air pollutants [34]. In order to investigate the relationship among air pollutants, risk index and influence factors, a redundancy analysis (RDA), which is a direct gradient analysis technique and has been widely used in environmental and ecological studies [5, 35]. The $K-S$ test and One-way ANOVA were performed by the software SPSS statistic 19.0, and RDA and PCoA were done by software Canoco 5.0.

Results and Discussion

General Characteristics of Air Pollutants

The mass concentrations of the air pollutants at four sites are shown in Fig. 2a). During the study period, the monthly concentrations of the $PM_{2.5}$ varied from 20-156 $\mu\text{g}/\text{m}^3$ with the average of 57 $\mu\text{g}/\text{m}^3$. For the PM_{10} , the values varied from 36-195 $\mu\text{g}/\text{m}^3$ with the mean of 95 $\mu\text{g}/\text{m}^3$. The SO_2 concentrations varied from 4-35 $\mu\text{g}/\text{m}^3$ with an average of 13 $\mu\text{g}/\text{m}^3$, and CO concentrations ranged from 0.355-2.303 mg/m^3 , 0.989 mg/m^3 . For the NO_2 and O_3 , the values ranged from 11-68 $\mu\text{g}/\text{m}^3$ (mean of 35 $\mu\text{g}/\text{m}^3$) and 33-205 $\mu\text{g}/\text{m}^3$ (mean of 106 $\mu\text{g}/\text{m}^3$). Through the $K-S$ test, the distributions of $PM_{2.5}$ and SO_2 values are disobedient normally distribution ($P < 0.05$), and may be the skewed distribution. From current study, the total pollution levels in the CPUA may have dropped compared with passed years since the policy of control emission was implemented in current years [31]. For example, the daily average concentration

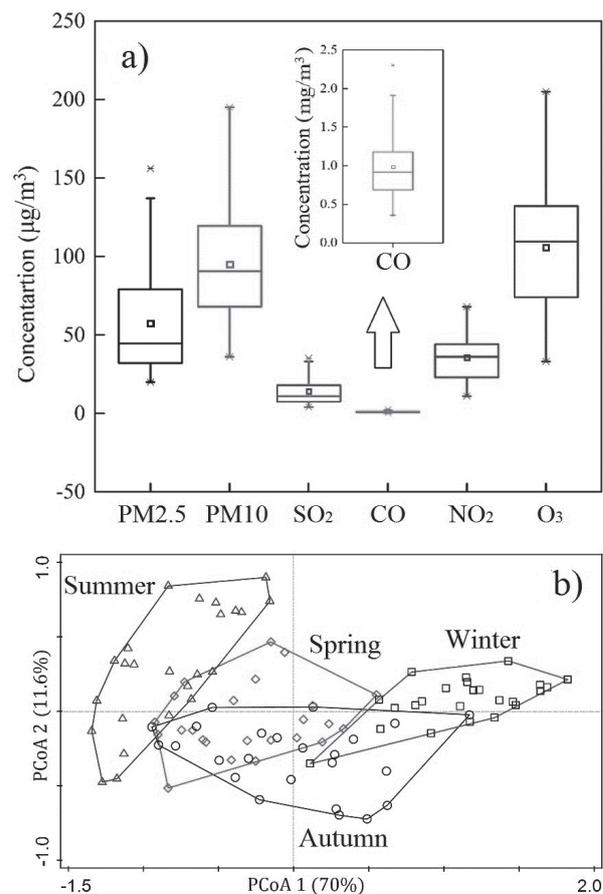


Fig. 2. The concentrations of air pollutant in the CPUA. a) In this box-whisker plots, the whiskers and boxes indicated the 95th, 75th, 50th (median), 25th and 5th percentiles, respectively. b) Principal coordinate analysis (PCoA) using the Bray Curtis matrix distance based on air pollutants data classified by season in the CPUA.

of PM_{2.5} observed in 2017 and the pollution days much less than those in 2014 to 2015 in Zhengzhou [36, 31].

As shown in Fig. 3, the monthly variations of most air pollutants over the two years were similar in the CPUA, the higher values were observed from November to next February, which also indicated that the air pollution event was related to these pollutants usually occurred in winter. In contrast, the lower values of O₃ were observed in the same period. The results of PCoA based on the air pollutants data also shown that the air pollution in winter was significant heavier than other seasons ($P < 0.05$), and the air pollution in summer was also significant lower than other seasons in the CPUA (Fig. 2b). These results are consistent with the previous studies in the CPUA [37]. It can be concluded that the fluctuating air pollutants may be the results from the influence of the driving factors changes in different season.

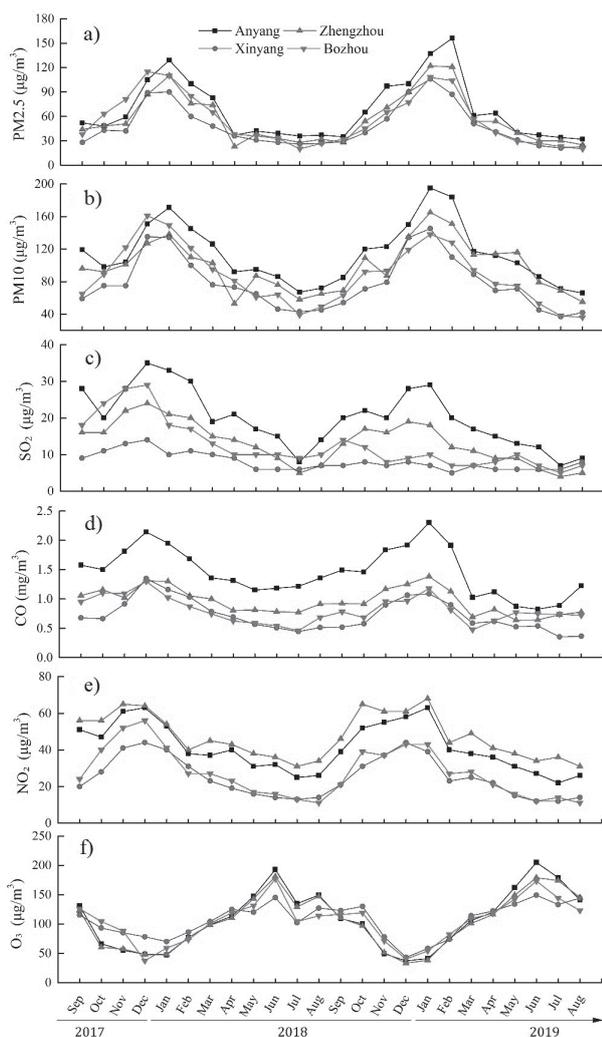


Fig. 3. Temporal variations in concentrations of air pollutants in the CPUA from September 2017 to August 2019.

AQI and AQHI

The AQHI was calculated according to the concentrations of multiple pollutants, and the results are shown in Fig. 4. The results shown that the tendency of AQHI varied with the month was similar with AQI in four cities of the CPUA. Obviously, the values were higher in winter than those in spring and summer. The AQHI presented stepped distribution, due to the AQHI was used as integers. According to the AQHI risk classification, the values were within the low and moderate risk in winter, such as the AQHI values in winter in Anyang and Zhengzhou were the moderate risk. These results indicated that the fluctuant AQHI varied with the pollutant concentration, and also influenced by other environmental factors. The reasons might be the pollutants variation were depended on environmental and emission factors. Nationally, a rise of one unit in AQHI, the mortality increase by 0.97%, which also vary by the age, gender and other factors [20]. Thus, the critical factors influencing AQHI, AQI and air pollutants should be ascertained.

Influencing Factors

The statistical results of environmental factors meteorological factors, such as rainfall amount,

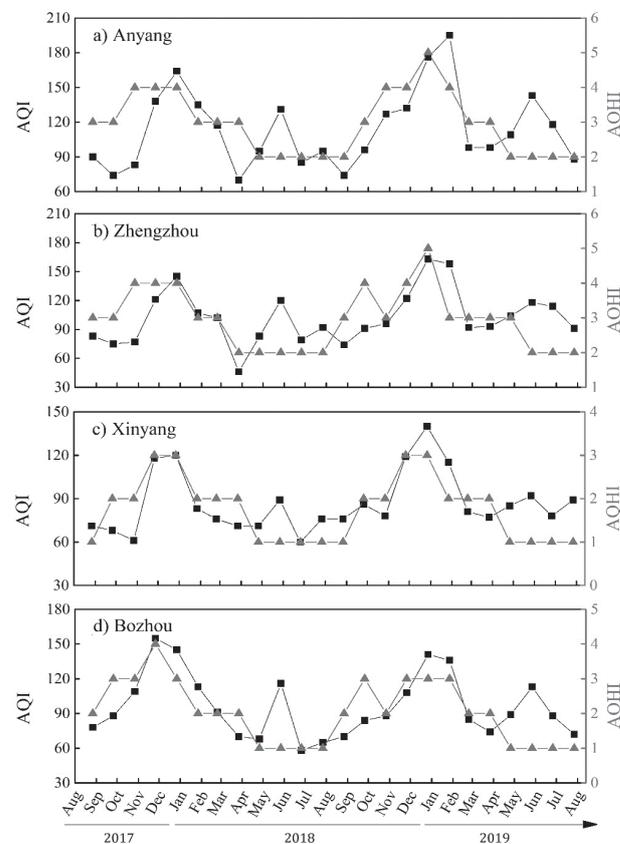


Fig. 4. Air Quality Index (AQI) and Air Quality Health Index (AQHI) in four cities of the CPUA. For the AQHI, low risk: 0-3, Moderate risk: 4-6, High risk: 6-9 and very high risk: >10.

atmosphere pressure, wind speed, air temperature, vapor pressure, relative humidity, precipitation days (>0.1 mm/d), sunshine duration, and social development indicators, such as industrial electricity consumption and total electricity consumption. The average monthly rainfall was 59.5 mm with a range from 0 to 254.4 mm during the study period in the CPUA. The rainfall concentrated mostly in Spring and Summer when the southeast monsoon carries rainwater into the plain area. Therefore, the number of precipitation days was often more in this periods than that in other seasons. Moreover, some meteorological factors varied with the season changes. Such as, atmosphere pressure, wind speed, air temperature, vapor pressure, air temperature and sunshine duration presented a regularly change pattern. These findings indicated that the interaction among these factors might play an important role in influencing materials transport and diffusion and these factors had different effects on the air pollution process.

The low electricity consumptions were observed in November and December, and the high electricity consumptions were recorded in July and August in the CPUA, the electricity consumption may increase with the increase of city size and population. Note that the total and industrial electricity consumption in four cities present similar annual tendency of variation, which suggesting some connections between the total and industrial electricity consumption.

Relationships Among Air Pollutants, Indices and Factors

Fig. 5 showed that the relations among air pollutants, AQI, AQHI and environmental factors in

the CPUA. As shown in Fig. 5, the Eigenvalues of the axis 1 and axis 2 were 0.68 and 0.06, the correlation coefficients between species and factors were 0.95 and 0.83 respectively. Two axes of RDA together explained 74.0% of the total variance, the axis 1 and axis 2 explained 67.6% and 6.4% of those, respectively. The correlation analysis shown that these factors, such as vapor pressure, air temperature, rainfall amount and precipitation days were significantly and positively correlated with axis 1, and negatively correlated with most air pollutants such as PMs, CO, SO₂ and NO₂, and AQHI and AQI ($P<0.01$), which indicated that increasing values of these factors could decrease the concentrations of most air pollutants and improve the air quality and population health. Conversely, these could increase the concentrations of O₃ in atmosphere. These results further suggesting that the RDA ordination axes can reflect well on the environment gradients.

Fig. 5b) showed the effects of environmental factors on the air pollution and air quality during winter in the CPUA. According to the former analysis, the air pollution event occurs most often during winter, especially for northeastern cities of Anyang and Zhengzhou. The Eigenvalues of the axis 1 and axis 2 are 0.59 and 0.12, correlation coefficients between species and factors are 0.94 and 0.86, respectively. The first 2 axes of RDA explained 70.9% of the total variance, the axis 1 and axis 2 explained 59.0% and 12.0%, respectively. Axis 1 was significantly correlated with vapor pressure, precipitation days, relative humidity, rainfall amount, industrial and total electricity consumption ($P<0.05$). The AQI, AQHI and most air pollutants were positively and significantly correlated with the industrial and total electricity consumption,

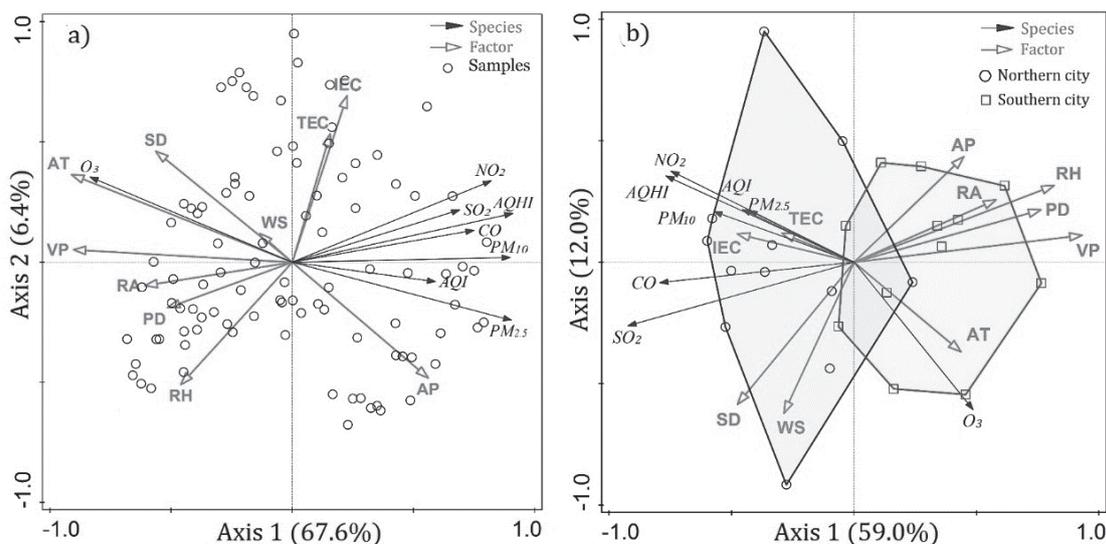


Fig. 5. Biplot of RDA showing the relationships between air pollutant, indices and environmental factors over two years a) and Winter b) in the CPUA. The red arrows represent environmental factors, and the blue ones represent the air pollutants and indices. RA: Rainfall amount, mm; AP: Atmosphere pressure, hPa; WS: Wind speed, m/s; AT: Air temperature, °C; VP: Vapour pressure, hPa; RH: Relative humidity, %; PD: Precipitation days >0.1 mm, d; SD: Sunshine duration, h; IEC: Industrial electricity consumption, billion kW h; TEC: Total electricity consumption, billion kW h. The length of arrows denotes the influencing degree of these selected factors on air pollutants and indices.

and negatively correlated with vapor pressure, precipitation days, relative humidity, rainfall amount. The Monte Carlo test showed that rainfall, vapor pressure and relative humidity were critical factors that influenced air pollution in winter. In addition, the results revealed the relationships between air pollution and environmental factors in northern and southern cities of the CPUA. The data were collected in the urban of four cities during winter and clearly clustered into two groups, namely, southern area and northern area. For example, in the northern area, the data of pollutant and air quality were closely linked to electricity consumption, and those were rainfall, vapor pressure and relative humidity for southern areas. Through the above analysis, the results indicated that rainfall, vapor pressure, relative humidity and electricity consumption were critical factors that affect the air quality and population health risk. Therefore, the air pollution and associated health risk in the CPUA were driven by various human activities, and also influenced by dominant meteorological factors.

The critical factors play an important role in driving the changes of air pollutants, the air quality and population health. In this study, most air pollutants present the significant and positive relations, except for the O_3 (Fig. 5), which were similar with previous studies. These may be due to the difference in environmental behavior among pollutants. As the result of previous studies, O_3 formation should be concerned when controlling $PM_{2.5}$, because of the O_3 is a secondary pollutant generated from photochemical reactions of some gaseous pollutants, such as, the oxy-nitride (NO_x) and volatile organic compounds (VOCs) [6, 38]. Additionally, the concentrations of pollutants can also influence the O_3 concentration, for example, due to the controlling of particular matters reduced the scattering and absorption of sunlight, increased UV radiation, and led to higher O_3 [6]. Furthermore, some factors are closely related to the O_3 concentration, for example, lower temperature can slow the photochemical reaction, and further decrease the O_3 concentration in the air. Many factors have higher relevance and particularity in temporal distribution, such as the rainfall activity (RA and PD) is likely to increase humidity (RH), and vapor pressure (VP), this can decrease the concentrations of most pollutants and further improve the air quality. In the CPUA, heavily influenced by monsoon climate, the volume of rainfall is quite unevenly distributed, causing rainstorm often to happen in summer, and the air temperature in the season is also higher. Therefore, the air pollution events tend to occur in winter, with the lower temperature, lower pressure, and less rainfall, which lead to form the steady atmospheric stratification and hinder the diffusion of pollutants and degradation [28]. In the study area, it has become an urgent problem how to control the air pollution in winter, improve the air quality and decrease the risk of population health.

In this study, we used the electricity consumption to represent the influences of human activities. The results showed that the air pollution or air quality was closely to the electricity consumption (Fig. 4.), suggesting that the impacts of human activities on air pollution can be well-represented by electricity consumption. The contribution of air pollutant from anthropogenic emissions to affect air quality and population health should not be neglected [39, 26]. The current study in the CPUA showed that the emissions of SO_2 , PM_{10} , $PM_{2.5}$, NO_x and CO are about 1.24, 1.29, 0.70, 1.93, 7.92 million tons, respectively, which come from the local region, particularly Zhengzhou and Pingdingshan [40]. In addition, the AQHI was used to represent the air quality, which can identify and develop new indicator to monitor air pollution-related health outcomes within surveillance systems. However, in some epidemiological cases, even the low concentration of some air pollutants is also harmful to population health [41, 13, 2]. Therefore, it is essential to establish the improved aggregate index including multiple air pollutants, such as O_3 , NO_x and VOCs, etc. Although a simple method was recommended to calculate the AQHI for assessing the air quality from the population health standpoint, which can also to fill gaps in the study of CPUA, which was believed can help understand the overall health impacts of multiple air pollutants.

Conclusions

In this study, current two-years data including multiple air pollutants, environmental factors were conducted at the four typical cities in the CPUA to determine the relationships among air pollutants, air quality, health risk and factors. The results showed that, the air pollutants presented the remarkable seasonal variations, according to the analysis of PCoA, the air pollution event often occurred in winter in the CPUA, and the AQHI were moderate risk for population health particularly in Zhengzhou and Anyang. The results of RDA showed that the air pollution and associated health risk in the CPUA was driven by human activities, and was influenced by dominant meteorological factors, such as, rainfall, vapor pressure, relative humidity. Our study provided a method to analysis the variations of multiple air pollutants and to explore the driving factors of pollution. The results provided meaningful understanding to formation mechanism of combined air pollution and possible emission control strategies in the CPUA, China.

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Conflict of Interest

The authors declare that they have no competing interests.

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