Front. Environ. Sci. Eng. 2021, 15(4): 74
https://doi.org/10.1007/s11783-020-1367-1

REVIEW ARTICLE

Health impacts of air pollution in China

Fengping Hu[1], Yongming Guo (✉)[2]

1 Business School, Nanjing University of Information Science & Technology, Nanjing 210044, China
2 Reading Academy, NUIST-UoR International Research Institute, School of Chemistry and Materials Science, Nanjing University of Information Science & Technology, Nanjing 210044, China

HIGHLIGHTS

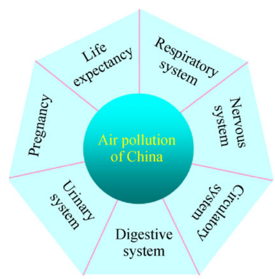
- Impacts of air pollution on various body systems health in China were highlighted.
- China's actions to control air pollution and their effects were briefly introduced.
- Challenges and perspectives of the health effects of air pollution are provided.

ARTICLE INFO

Article history:
Received 6 March 2020
Revised 6 September 2020
Accepted 21 September 2020
Available online 15 November 2020

Keywords:
Health impacts
Air pollution
China
Advances

GRAPHIC ABSTRACT



ABSTRACT

The health effects of air pollution have attracted considerable attention in China. In this review, the status of air pollution in China is briefly presented. The impacts of air pollution on the health of the respiratory system, the circulatory system, the nervous system, the digestive system, the urinary system, pregnancy and life expectancy are highlighted. Additionally, China's actions to control air pollution and their effects are briefly introduced. Finally, the challenges and perspectives of the health effects of air pollution are provided. We believe that this review will provide a promising perspective on the health impacts of air pollution in China, and further elicit more attention from governments and researchers worldwide.

1 Introduction

Fresh air is of great significance for human life. However, with the rapid development of modern industrialization, the air quality around us is increasingly affected, especially in developing countries, such as China and India. The WHO has estimated that approximately 2.4 million people die of diseases related to air pollution per year worldwide (Li et al. 2019b). Therefore, air pollution has generated considerable attentions at a global level. At the same time, the Chinese government and related researchers have recently begun to pay close attention to air pollution and its effects. In particular, the impacts of air pollution on human health in China have been explored, and considerable achievements have been made (Zhang et al. 2010; Yu et al. 2013; Lin et al. 2017; Niu et al. 2017; Liu et al. 2018; Yang et al. 2020a). Therefore, a review presenting the health effects of air pollution in China is urgently needed and may be meaningful for the related researchers and governments.

In the remainder of this paper, we first outlined the status of air pollution in China. Then the health impacts of air pollution in China are provided in the 3rd section; we respectively analyzed the impacts of air pollution on the health of the respiratory system, circulatory system, nervous system, digestive system, urinary system, and pregnancy (Fig. 1). In the 4th section, China's actions to control air pollution and its effects are briefly introduced. In the conclusion section, we present the challenges and perspectives of the health effects of air pollution.

2 Air pollution status in China

In China, the main air pollutants present are sulfur dioxide

✉ Corresponding author
E-mail: yongmingguo@nuist.edu.cn, chinahenangm@163.com

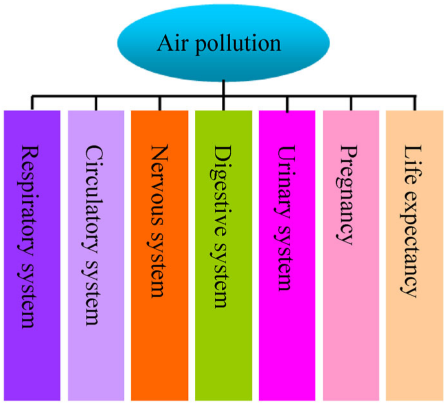


Fig. 1 Summary of the health impacts of air pollution in China.

(SO_2), carbon monoxide (CO), nitrogen oxide (NO_x), ozone (O_3), polycyclic aromatic hydrocarbons (PAHs), particulate matter (PM) and so on (Song et al. 2017). Specifically, SO_2 is a type of highly irritating toxic gas, which comes mainly from the combustion of raw coal and other fuels containing sulfur. CO is the product of incomplete combustion of carbon-containing fuels. NO_x is mainly derived from the emissions of motor vehicles and the combustion of nitrogen-containing compounds. Ozone comes from the chemical reactions of CO, NO_x and other compounds in sunlight (Sáenz-de-Miera 2013). PAHs are mainly emitted from coal combustion, traffic and biomass combustion in China (Zheng et al. 2019). And PMs mainly come from direct emissions from combustion, such as power plant and diesel engine exhausts. These air pollutants have been confirmed to be toxic to human health.

Because China is a coal-burning country, the levels of SO_2, NO_x and total suspended particulates (TSP) in the air are higher than those in many other countries. In the period of 1995–2014, the levels of SO_2 and TSP exhibited a downward trend. However, the concentration of NO_x remained stable. And the particulate matter with aerodynamic diameter ≤2.5 µm ($PM_{2.5}$) and O_3 levels further increased even in central and eastern China, which should receive close attention because $PM_{2.5}$ and O_3 are more harmful to human health than that of SO_2 and NO_x (Jin et al. 2016; Ruan et al. 2019). These pollutant distributions exhibited spatiotemporal differences. Yang et al. demonstrated that emissions and meteorological variations mainly affected the air quality in western China. They measured six air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3) at 23 sites in western China for 1 year and observed that over highly populated mega-city regions, such as Sichuan and Guanzhong basins, there are high pollutant concentrations, and the Tibetan Plateau exhibited low levels of pollutants. At the same time, these pollutants also had seasonal distribution variations. The concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2 and CO were high in winter and low in summer, whereas the level of O_3 in low-altitude regions showed the opposite seasonal trends. An increasing trend was still persistent in O_3 concentrations. Moreover, lighting and stratospheric transmission may have led to the gradual increase in NO_2 levels in the upper atmosphere (Yang et al. 2020b). Zhao's group performed a comprehensive analysis of the spatiotemporal variation of urban air pollution in China based on the data of more than 300 cities from May 2014 to December 2018. They observed that the air pollutants exhibited distinct spatial distribution variations with high levels of NO_2 in North China and East China, high levels of CO in North China and North-west China, high levels of SO_2 in North China and North-east China, high levels of $PM_{2.5}$ in North China and Central China and high levels of PM_{10} in North-west China. The worst regions for air pollution were the North China Plain and in cities in central and western Xinjiang Province. These spatial distributions may be attributed to differences in emissions (Fan et al. 2020a). In addition, Miao et al. analyzed a panel of data for 30 provinces in China and concluded that the regional atmospheric environmental inefficiency was related to SO_2 emissions from industrial soot and NO_x emissions from vehicle exhaust (Miao et al. 2019). Comfortingly, green space is able to reduce air pollution because the leaves of vegetation can absorb gaseous pollutants and induce the deposition of PMs (Kumar et al. 2019). For instance, Wang's group observed that street trees may contribute more to reducing air pollution than grasses in terms of the analysis of the relationship between residential greenness, air pollution and the psychological well-being of urban residents in Guangzhou, China (Wang et al. 2019d).

Notably, the Chinese government has taken various measures to control air pollution in the past few years, resulting in great changes in the levels of air pollutants. The levels of PMs, SO_2 and NO_x were reduced. For example, from 2013 to 2016, the annual country-wide mean PM_{10} and $PM_{2.5}$ levels significantly dropped by 29% and 42%, respectively, though the concentrations were still higher than the WHO guidelines. Additionally, NO_x and SO_2 decreased by 42% and 50%, respectively. However, O_3 concentrations are still increasing throughout the country, and strict strategies should be taken to control air pollution (Zeng et al. 2019b). In urban areas, the annual average levels of $PM_{2.5}$, PM_{10}, SO_2, and CO declined from 2015 to 2019. However, the annual mean concentration of O_3 increased, and the rate of increase was nearly 14 times that of the global rate (Fan et al. 2020b). However, the PAHs levels were distributed differently in different places in China. For example, the PAHs concentrations in Beijing and Taiyuan first exhibited an increasing tendency and then a decreasing tendency, whereas a decreasing tendency was observed in the concentrations of particulate PAHs in Nanjing and Guangzhou during 2000–2015 (Yan et al. 2019).

Therefore, the air pollution in China exhibited distinct differences in spatial and temporal distributions, which may be related to emissions, meteorological variations, geographical differences, human activities and government policies.

3 Effects of air pollution on human health in China

A number of epidemiological studies have shown that air pollution was closely related to a variety of diseases and causes of death, such as respiratory diseases, circulatory diseases, nervous diseases, digestive diseases, and urinary diseases. Even with some birth defects, serious developmental delays in infants are also related to air pollution (González-Díaz et al. 2016; Guan et al. 2016). And our life expectancy is also affected by air pollution. The impacts of air pollution on human health are divided into short-term and long-term effects, for instance, emergency hospital visits, outpatient visits and hospitalizations for respiratory diseases, cardiovascular diseases, and nervous diseases are short-term effects. The long-term impact includes the mortality of various diseases (Guan et al. 2016). Thus, air pollution has shown serious impacts on human health.

3.1 Respiratory system

The respiratory system is necessary for human life. Polluted air could harm the respiratory system. The short-term effects of air pollution on the respiratory system include emergency hospital visits, outpatient visits and hospitalizations for respiratory diseases, childhood respiratory diseases, lung function decrement, tuberculosis, and measles. The long-term effects consist of respiratory morbidities, lung function impairment, acute nasopharyngitis, lung cancer mortality and so on. The impacts on respiratory diseases vary by factors such as air pollutants, sex, age, seasons, and regions.

Studies have suggested that air pollution could increase the risks of emergency hospital visits, outpatient visits and hospitalizations for respiratory causes. Recently, the associations between ambient air pollutants and emergency hospital visits in China were examined at the national level, and the corresponding attributable risks were evaluated by a multi-city study on the basis of quasi-Poisson regression model with a constrained distributed lag model and a random-effect meta-analysis. The investigators noticed that daily emergency hospital visits were significantly correlated with $PM_{2.5}$ and PM_{10}, NO_2 and SO_2. Exposure to $PM_{2.5}$, PM_{10}, NO_2 and SO_2 resulted in emergency hospital visits of 3.34%, 3.96%, 5.90% and 5.38%, respectively (Chen et al. 2017b). A recent report based on the analysis of a generalized additive model with a quasi-Poisson regression model indicated that exposure to ambient CO contributed to an increased risk of respiratory outpatient visits in Dongguan, China, particularly, females and the elderly population were particularly vulnerable (Zhao et al. 2019). Additionally, a study from Zhang's group based on the analysis of a time-stratified case-crossover model and conditional logistic regression model indicated that PM_1 and $PM_{2.5}$ significantly increased the chances of hospital admission for pneumonia and chronic obstructive pulmonary diseases, but had no influence on asthma and upper respiratory tract infection. Stronger impacts were observed in subjects aged 0–14 years and 45–74 years. The effects of PM_1 and $PM_{2.5}$ mainly occurred in the cold season (Zhang et al. 2019b).

The associations of air pollution and respiratory hospitalizations in Lanzhou, China were demonstrated on the basis of the analysis of the data in 2001–2005 by using Poisson regression models. The three air pollutants (SO_2, NO_2 and PM_{10}) had a lag effect on hospital admissions for respiratory diseases: for SO_2, NO_2, PM_{10}, the lag was 1–3 days, 1–4 days, and 3–5 days, respectively. The relative risks (139 $\mu g/m^3$ for PM_{10}, 61 $\mu g/m^3$ for SO_2 and 31 $\mu g/m^3$ for NO_2) were calculated for increases in the interquartile range. Moreover, air pollution exhibited much stronger impacts on female individuals and aged$\geqslant$65 years in Lanzhou (Tao et al. 2014). Additionally, the impacts of $PM_{2.5}$ on respiratory diseases in Lanzhou, China were explored using a distributed lag nonlinear model. $PM_{2.5}$ was related to increased daily hospitalization for respiratory diseases in Lanzhou. Importantly, the cumulative effect of $PM_{2.5}$ on the number of respiratory outpatient visits was greater than its daily effect, and the cumulative effect peaked on day 12. Moreover, females and people aged 18 years or younger have a higher risk of respiratory outpatient visits (Chai et al. 2019).

Air pollution also showed short-term negative effects on lung function. A study from the Wuhan-Zhuhai cohort in China demonstrated that air pollution had a short-term adverse effect on the lung function of female non-smokers based on linear mixed model. The moving averages of NO_2, PM_{10}, and $PM_{2.5}$ concentrations markedly contributed to forced vital capacity (FVC) reduction. In high pollution cities, the moving average of NO_2, PM_{10}, O_3, and $PM_{2.5}$ exposures corresponded to reductions in FVC and forced expiratory volume in one second (FEV_1). In cities at low pollutant levels, PM_{10} (Lag03–Lag05) and O_3 (Lag01–Lag03) were remarkably correlated with reduced FVC, whereas PM_{10} (Lag03–Lag05), O_3 (Lag0–Lag03), and $PM_{2.5}$ (Lag04–Lag06) were notably correlated with decreased FEV_1 (Zhou et al. 2016). Additionally, the short-term impacts of air pollution on lung function in patients with chronic obstructive pulmonary disease (COPD) patients were studied in Beijing, China from December 2015 to September 2017. The findings showed that $PM_{2.5}$, NO_2, SO_2 and CO contributed to decreased FVC % predicted in COPD patients, which have been attributable to increased Th1 and Th17 cytokines and decreased Th2 cytokines (Gao et al. 2020).

Air pollution is also associated with childhood respiratory diseases. Liu et al. conducted a cross-sectional study in 2011-2012 in Shanghai, China; 3,358 preschool children who did not change their residences after birth were evaluated by utilizing logistic regression models. They observed that lifetime exposure to NO_2 was significantly related to childhood allergic rhinitis. There were no significant correlations of SO_2, PM_{10} or their combination with the disease. However, SO_2 and PM_{10} did strengthen the effect of ambient NO_2 on childhood respiratory health (Liu et al. 2016b). Additionally, Shi's group has demonstrated the short-term impacts of ambient air pollution on pediatric respiratory outpatient visits in Yichang, China, by analyzing the data from 2014 to 2015 using generalized additive Poisson models. They observed that the four air pollutants ($PM_{2.5}$, PM_{10}, NO_2, CO) exposures (no lag) contributed to pediatric respiratory outpatient visits and O_3 exposure (lag 4 days) accounted for increased risks of pediatric outpatient visits for respiratory diseases. Furthermore, the change in season did not alter these correlations (Liu et al. 2017c). The impacts of air pollution on child upper respiratory tract infection (URTI) outpatient visits were also examined by using a generalized additive model to study the lag effects between daily changes in air pollutants and the number of hospital outpatient visits aged 0–14 years with URTI from 2014 to 2015 in Hefei, China. They found that air pollution was associated with an increase in child URTI outpatient visits. In particular, NO_2 contributed most to increased risk of child URTI outpatient visits (Li et al. 2018). The short-term impacts of NO_2, O_3, PM_{10} and $PM_{2.5}$ on childhood asthma hospitalization have been studied using Poisson generalized linear regression combined with a distributed lag nonlinear model to analyze 17,227 childhood asthma hospital visits during 2015–2016 in urban areas of Hefei, China. These air pollutants showed adverse impacts on asthma admissions for children, and NO_2 appeared to be the most important risk factor, followed by $PM_{2.5}$ (Zhang et al. 2019c).

Air pollution also exhibited short-term adverse impacts on children's lung function. A study conducted in Taiwan, China found that short-term exposure to O_3 and PM_{10} could lead to FVC and FEV1 reductions. CO and SO_2 exposure showed a greater effect on FVC and FEV1 with a 1-day lag (Chang et al. 2012). Additionally, a study of 334 healthy children (7–11 years) from four cities (Chengdu, Guangzhou, Wuhan and Xi'an) in China from 2014 to 2016 revealed that exposure to $PM_{2.5}$ and PM_{10} showed a short-term effect on the lung function decrement of primary school-aged children. Girls were more sensitive than boys (Chen et al. 2018a). Moreover, Chen et al. found that PAHs and benzene, toluene, ethylbenzene and 1,2-dimethylbenzene exposure near the coal-chemical industry in Northern China led to declined child lung function (Chen et al. 2018c). Additionally, Fan's group noticed that co-exposure to PAHs, benzene and toluene might damage the lung function of asthmatic children by increasing oxidative damage and airway inflammation (Kuang et al. 2020). These results reveal that children are easily affected by air pollution; thus children should avoid exposure to air pollutants as much as possible.

Some infectious respiratory diseases are also related to air pollution. Tuberculosis (TB) is a serious infectious respiratory disease that easily causes death. A number of studies have suggested that air pollution is associated with tuberculosis (Popovic et al. 2019). For example, the relationship between ambient air pollutants and newly diagnosed tuberculosis in 2010–2015 in Chengdu, China was studied using a distributed lag nonlinear model. The results revealed that PM_{10}, NO_2 and SO_2 exhibited a positive impact on the incidence of TB, and sex and age did not modify this effect. Moreover, SO_2 only showed remarkable impacts in males (Zhu et al. 2018). A recent study conducted by Li et al. suggested that exposure to ambient $PM_{2.5}$, PM_{10}, SO_2, and NO_2 increased the risk of active tuberculosis. In addition, ambient air PM_{10} and NO_2 showed a significant effect on the risk of tuberculosis (Li et al. 2019b). Measles also is another type of infectious respiratory disease. Exposure to $PM_{2.5}$ significantly increased the risks of measles incidence in 21 cities of China based on a Poisson regression model, a constrained distributed lag model and a random-effect meta-analysis. An increased risk of measles incidence lagged with $PM_{2.5}$ was observed at 1–3 days. Additionally, high temperature, low humidity, and high wind speed also strengthen the associations (Chen et al. 2017a).

The long-term impacts of air pollution on the respiratory system have been explored. Wong's group has performed a cross-sectional study among Chinese children aged 8–10 years in Hong Kong, China to investigate the relationships between long-term exposure to PM_{10}, SO_2, NO_2 and O_3 and lung function. Important findings were observed: long-term exposure to higher ambient air pollutants significantly contributed lower lung function among boys, PM_{10} was the most relevant pollutant responsible for lung function impairment, and asthmatic children were more sensitive to exposure to air pollution (Gao et al. 2013). They further conducted a cross-sectional study to evaluate the long-term effect of air pollution on Chinese child respiratory morbidities among 2,203 school children between the ages of 8 and 10 in three districts with different air pollution levels in Hong Kong, China. They observed that PM_{10} may have contributed mostly to wheezing and phlegm in boys. Both PM_{10} and NO_2 may have caused cough and phlegm in girls (Gao et al. 2014). Additionally, long-term exposure to air pollutants (PM_{10}, SO_2, NO_2 and O_3) could increase the odds of pulmonary function impairment in Chinese children in the seven highly polluted north-eastern cities of China based on two-stage regression models. Females have a higher risk of lung function impairment than males (Zeng et al. 2016). Hou et al. have also explored the long-term exposure to $PM_{2.5}$ and NO_2 on lung function among 5,276 permanent residents aged ⩾20 years in Shanghai, China, by utilizing multivariable linear regression, adjusting for potential confounders. They found that exposure to higher levels of $PM_{2.5}$ and NO_2 significantly contributed to lung function impairment, including lower forced vital capacity, inspiration capacity, and vital capacity (Hou et al. 2020). The results reveal that air pollution yields long-term adverse effects on lung function, especially for girls.

COPD, one of the many noncommunicable diseases with high morbidity and mortality, has aroused considerable attention (Buist et al. 2007). An increasing number of reports have demonstrated that air pollution is strongly associated with COPD (Duan et al. 2020). A cross-sectional study in four cities across Guangdong Province of China revealed that long-term exposure to higher PM concentrations was strongly connected with increased COPD prevalence and decreased respiratory function (Liu et al. 2017b). A longitudinal, cohort study in Taiwan, China demonstrated that long-term exposure to $PM_{2.5}$ was associated with decreased lung function and increased the risk of COPD (Guo et al. 2018a).

Air pollution has also been shown to influence the longevity of people with other diseases. Accumulating evidence has shown that air pollution is associated with lung cancer mortality. Zhu and his coworkers found that air pollution could significantly increase respiratory disease and lung cancer mortality based on a time-series analysis of 10,388 subjects in 2009–2015 in Hefei, China. An increase of 10 $\mu g/m^3$ in SO_2, NO_2 and PM_{10} accounted for 4.38%, 7.69%, and 1.55% increases in respiratory disease mortality, respectively. However, lung cancer mortality was only significantly related to SO_2 level (Zhu et al. 2019). The short-term impacts of ambient air pollution on lung cancer mortality were studied by utilizing time-series generalized linear models. They found that short-term exposure to air pollution increased the risk of lung cancer mortality. The short-term associations varied by city and season. Specifically, high concentrations of $PM_{2.5}$, PM_{10}, and O_3 in the warm season in Beijing, and high levels of $PM_{2.5}$, PM_{10}, and SO_2 during the cool season in Chongqing and Guangzhou accounted for increased lung cancer mortality. Moreover, male and elderly lung cancer patients were more sensitive to air pollution (Wang et al. 2019c). Moreover, there may be some factors that may synergistically worsen the effects of air pollution on mortality. Sun et al. examined the short-term impacts of air pollution modified by urban climate on pneumonia mortality in Hong Kong, China by employing a case-crossover analysis method. An increasing linear trend of urban climate modification on the association of pneumonia mortality with NO_2 was observed. Therefore, the authors they concluded that a warmer urban climate could worsen the acute mortality effects of pneumonia associated with air pollution in Hong Kong, China (Sun et al. 2019). Moreover, a national-scale assessment of the association between cancer risk and atmospheric PAHs in 11 cities across China revealed that dermal contact exposure and inhalation exposure to PAHs might cause potential cancer risk (Ma et al. 2020).

The results suggested that respiratory system health is closely associated with air pollution. The severity of the impacts of air pollution depends on types and concentrations of the air pollutants, regions, climate, sex and so on. In particular, children, females, and males with respiratory diseases are more susceptible to air pollution. To better compare the effects of air pollution on respiratory system, a brief summary is exhibited in Table 1, the indicate effects observed in China are similar to those observed in Iran (Karimi et al. 2019).

3.2 Circulatory system

The circulatory system is one of the most important systems for normal functions of human beings. It is a continuous closed tubular system distributed throughout all parts of the body, including cardiovascular system and lymphatic system. Recent studies revealed that air pollution can affect circulatory system health, worsening or inducing circulatory diseases, including elevated blood pressure, hypertension, emergency outpatient visits and hospital admissions for circulatory diseases, cardiovascular mortality and so on. Notably, although blood pressure is also associated with the nervous system, blood pressure is still categorized as part of the circulatory system, which may be because blood pressure alterations correspond to impairment or damage of the circulatory system (Boudier et al. 1992; Levy et al. 2001; Louwies et al. 2015; Xia et al. 2017). For instance, Li's group has demonstrated the impacts of long-term exposure to air pollution on the blood pressure of 39,259 participants in five rural regions of central China by employing satellite-based spatiotemporal models and mixed-effect regression models. They noticed that each 1 $\mu g/m^3$ increase in $PM_{2.5}$, PM_{10} and NO_2 caused the adjusted odds ratio of hypertension to be 1.029, 1.015 and 1.069, respectively. The effect of NO_2 was more pronounced than that of $PM_{2.5}$ and PM_{10}. In addition, the hypertensive impacts of air pollution were larger among males, smokers, drinkers, high-intensity exercisers and high-fat dieters (Li et al. 2020).

Hypertension is easily found in people of all ages, and is very dangerous to lifetime health. Liu and coworkers conducted a nationwide cross-sectional study about the impacts of ambient $PM_{2.5}$ on hypertension in China using multivariable logistic regression models and linear regression models. They observed that $PM_{2.5}$ exhibited stronger impacts on hypertension prevalence among middle-aged, obese and urban participants. A national study suggested that long-term exposure to $PM_{2.5}$ contributed to an increase in the prevalence of hypertension in China (Liu et al. 2017a). Additionally, the associations of long-term exposure to ambient PM_1 with hypertension and blood pressure in rural Chinese populations were demonstrated

Table 1 Summary of air pollution on the health of the respiratory system

Impacts on health	Air pollutants	References
Respiratory emergency hospital visits	$PM_{2.5}$, PM_{10}, NO_2, SO_2	Chen et al., 2017b
Respiratory outpatient visits	CO	Zhao et al., 2019
Respiratory hospital admission	PM_1, $PM_{2.5}$	Zhang et al., 2019b
Respiratory hospitalizations	SO_2, NO_2, PM_{10}	Tao et al., 2014
Daily respiratory outpatient visits	$PM_{2.5}$	Chai et al., 2019
Lung function of female non-smokers	NO_2, PM_{10}, $PM_{2.5}$	Zhou et al., 2016
COPD	$PM_{2.5}$, NO_2, SO_2, CO	Gao et al., 2020
Childhood allergic rhinitis	NO_2, SO_2, PM_{10}	Liu et al., 2016b
Paediatric respiratory outpatient visits	$PM_{2.5}$, PM_{10}, NO_2, CO, O_3	Liu et al., 2017c
Hospital outpatient visits for child upper respiratory tract infection	NO_2	Li et al., 2018
Child asthma hospitalization	NO_2, O_3, PM_{10}, $PM_{2.5}$	Zhang et al., 2019c
Child lung function	O_3, PM_{10}, CO, SO_2	Chang et al., 2012
Child lung function	$PM_{2.5}$ and PM_{10}	Chen et al., 2018a
Child lung function	PAHs, benzene, toluene, ethylbenzene, 1,2-dimethylbenzene	Chen et al., 2018c
Lung function of asthmatic children	PAHs, benzene, toluene, ethylbenzene, 1,2-dimethylbenzene	Kuang et al., 2020
Tuberculosis	PM_{10}, NO_2, SO_2	Zhu et al., 2018
Active tuberculosis	$PM_{2.5}$, PM_{10}, SO_2, NO_2	Li et al., 2019b
Measles	$PM_{2.5}$	Chen et al., 2017a
Lung function	PM_{10}, SO_2, NO_2, O_3	Gao et al., 2013
Child respiratory morbidities	PM_{10}, NO_2	Gao et al., 2014
Child lung function	PM_{10}, SO_2, NO_2, O_3	Zeng et al., 2016
Lung function	$PM_{2.5}$ and NO_2	Hou et al., 2020
COPD	PM	Liu et al., 2017b
COPD	$PM_{2.5}$	Guo et al., 2018a
Respiratory diseases mortality, lung cancer mortality	SO_2, NO_2, PM_{10}	(Zhu et al., 2019
Lung cancer mortality	$PM_{2.5}$, PM_{10} O_3, SO_2	Wang et al., 2019c
Pneumonia mortality	NO_2	Sun et al., 2019
Potential cancer risk	PAHs	Ma et al., 2020

based on a satellite-based spatiotemporal model and multivariable linear regression model. The findings indicated that PM_1 was linked to an increase in the risk of hypertension and elevated blood pressure. This effect was more pronounced in males and those with unhealthy habits (Li et al. 2019a).

Recent studies have shown that air pollution is connected with an increase in the risk of emergency hospital visits and daily hospital admissions for circulatory diseases. Guo et al. demonstrated the short-term impacts of air pollution on circulatory emergency department visits in 2013–2015 in Guangzhou, China, by employing Poisson generalized additive models. They found that an increase in SO_2 level (per 7.98 μg/m^3) was related to a 5.19% elevation in emergency department visits for circulatory diseases. The effect was more obvious in the cold season (Guo et al. 2018b). The associations of ambient PM and hospital outpatient visits for cardio-cerebrovascular disease (CCD) in Nanjing, China, were evaluated based on a time-series study. They found that a 10 μg/m^3 increase in $PM_{2.5}$ and PM_{10} levels on the current day of exposure accounted for 0.42% and 0.37% increases in CCD. The estimated risks in the warm season were larger than those in the cold season, indicating that ambient PM pollution and temperature may have potential synergistic effects on CCD (Wang et al. 2019a). In addition, the impacts of air pollution on daily hospital admissions for cardiovascular diseases in Wuhan, China, during the period of from 2013 to 2015 were examined using a generalized additive model. The results suggested that $PM_{2.5}$, SO_2 and NO_2 contributed most to the increased risk of cardiovascular hospital admissions, and an increase of 10 μg/m^3 for

$PM_{2.5}$, SO_2 and NO_2 was related to 0.87%, 3.41% and 2.98% increases in hospital admissions for cardiovascular diseases (Wang et al. 2018a).

Cardiovascular diseases are serious diseases that are the leading cause of death globally. Many studies have demonstrated that ambient air pollution contributes to an increased risk of cardiovascular diseases. Ma's group assessed the associations between $PM_{2.5}$ and cardiovascular diseases in the Beijing metropolitan area in 2009–2012 using a generalized additive model. They observed that the increase in $PM_{2.5}$ concentration contributed the number of hospital emergency room cardiovascular visits. And the short-term impact of $PM_{2.5}$ on the incidence of cardiovascular diseases was the highest for the subgroup aged 60–75 years. Moreover, the short-term impact of $PM_{2.5}$ on ischemic heart disease and high blood pressure was relatively larger for females than for males (Ma et al. 2019).

Diabetes disease causes the body to metabolize glucose abnormally. Recent studies suggested that diabetes was positively associated with air pollution (Yang et al. 2020a). For example, a time-series study conducted in Shijiazhuang, China based on an adjusted over-dispersed passion generalized addictive model revealed the acute effect of six air pollutants on type II diabetes mellitus (T_2DM) hospitalization. Specifically, a 10-μg/m^3 increase in $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO elevated T_2DM hospitalization by 0.53%, 0.32%, 0.55%, 1.27%, and 0.04%, respectively. Stronger impacts were observed in the cold season. The male and elderly (⩾65 years) populations were more sensitive to these air pollutants (Song et al. 2018a). Also, Yang's group has noticed that PM_{10} exhibited an acute effect on diabetes mortality based on a study from 16 Chinese provincial cities during 2007–2013. The impacts were limited to 3 days. PM_{10} showed a harvesting effect on diabetes mortality during lags 4–10 days. The effect appeared to be stronger among males and the elderly population aged 75 or over (Yang et al. 2020c). Long-term effects of air pollution on diabetes were also observed in a nationwide cross-sectional study from June 2011 to March 2012. Specifically, an interquartile range increase in $PM_{2.5}$ corresponded to elevated T_2DM prevalence, and increased levels of fasting glucose and HbA1c (Liu et al. 2016a). Yang et al. found that long-term exposure to PM_1, $PM_{2.5}$ and PM_{10} corresponded to the increased risk of diabetes in a Chinese population, particularly in younger or overweight or obese individuals, based on results from a large cross-sectional study in three cities of Liaoning Province, China, that utilized a random number generator and a four-stage, stratified and cluster sampling strategy (Yang et al. 2018).

Importantly, air pollution has been confirmed to be significantly linked with mortality from all causes. Recently, Li's group used generalized additive Poisson regression to evaluate the relationships between exposure to ambient air pollution and mortality from all causes, pneumonia, and congenital heart diseases among children under 5 years old in Beijing, China. They revealed that ambient air pollution exhibited a positive impact on deaths among children aged < 5 years in Beijing, China, and SO_2 and NO_2 might be the best indicators of the relationships between air pollution and these deaths. In particular, children with congenital heart diseases are more sensitive to air pollution (Wang et al. 2019b). Wang et al. studied the relationships between ambient coarse particle pollution (PM_c) and cardiovascular mortality in three Chinese cities of the Pearl River Delta region in 2013–2016 utilizing generalized additive models. The results indicated that each 10 μg/m^3 increment in the current day's PM_c contributed to a 1.63% increase (95% CI: 0.31%, 2.98%) in cardiovascular mortality, revealing that PM_c might be a significant air pollutant (Wang et al. 2018b). The effects of short-term exposure to ambient particulate matter on cause-specific death in Changzhou, China during the period of 2015-2016 were studied by Zhang's group. They noticed that PMs exhibited the strongest impacts on hypertensive mortality, with a 10 μg/m^3 increase in $PM_{2.5}$ and PM_{10} accounted for increases of 5.27% and 3.52%, respectively. Elderly individuals were vulnerable to PMs. Moreover, females were sensitive to circulatory, hypertensive and respiratory mortality. Males were vulnerable to chronic lower respiratory and neurodegenerative death. The associations were stronger in warm seasons (Yu et al. 2019). The connections between air pollution and cardiovascular mortality in Hefei, China between 2010 and 2015 were also assessed using time-series analysis in generalized additive model. The findings suggested that both PM_{10} and SO_2 accounted for cardiovascular mortality, and women were more sensitive to air pollution than men (Zhang et al. 2017).

Recently, the concentration of ambient O_3 in China has increased year by year. Thus the impacts of O_3 on health have attracted great attention. Zhang et al. have explored the acute effects of O_3 on daily cardiovascular disease mortality from 2015 to 2017 in Jiangsu, China using the time-series model linked with Poisson distribution. They observed that 3-day moving average O_3 exerted the strongest effect on cardiovascular mortality, and each 10 μg/m^3 in O_3 increased the cardiovascular mortality by 0.98% (Zhang et al. 2019a).

Regarding the intrinsic reasons for the harmful effects of air pollution on circulatory system health, much evidence from epidemiological studies, controlled exposures in human subjects, in vivo animal models and in vitro assays have revealed that oxidative stress plays a significant role in circulatory system diseases induced by exposure to air pollution (Miller 2020).

From the abovementioned results, we can see that exposure of ambient air pollution has exhibited adverse impacts on our circulatory system. In particular, NO_2, SO_2, O_3, $PM_{2.5}$, PM_{10} and PM_c have the largest impacts on the cardiovascular systems; these effects are similar to the air pollution effects on cardiovascular diseases in Bangkok, Thailand (Phosri et al. 2019). The impacts of air pollution on circulatory system health are briefly summarized the in Table 2.

3.3 Nervous system

The nervous system is the system that regulates the body's physiologic function, it is mainly composed of nervous tissues. The nervous system, which is of great importance for normal human activities, is divided into central nervous system and peripheral nervous system. Considerable studies have suggested that ambient air pollution contributes to the disorders of the nervous system, such as sleep disorders, sleeplessness, hospital admissions and visits for nervous diseases, suicide attempts, Parkinson's disease (PD), Alzheimer's disease (AD), and some eyes diseases.

With the rapid development of our society, we do not sleep as well as we used to. Among the contributing factors, air pollution is an important issue. The associations of air pollution with poor sleep quality from 2015 to 2017 in Henan rural populations, China were estimated based on the Pittsburgh sleep quality index. The results revealed that long-term exposure to NO_2 and $PM_{2.5}$ was related to poor sleep quality in rural China (Chen et al. 2019b). The effects of air pollution on sleep disorders among elderly residents aged>60 in Ningbo, China during the period of 2008-2017 were assessed by employing a generalized additive model. The findings suggested that air pollution exhibited a positive impact on sleep disorders, and the strongest influences of traffic-related pollutants (NO_2, SO_2, O_3, $PM_{2.5}$ and PM_{10}) were observed with lags of 2-3 days (Tang et al. 2019). Recently, the associations of air pollution with sleeplessness in Chinese cities were demonstrated by utilizing the ordinary least square model. One standard deviation increases in AQI and $PM_{2.5}$ were associated with approximately 11.6% and 12.8% increases in sleeplessness, respectively. These findings provided that air pollution could cause a decrease in sleep quality (Heyes and Zhu 2019).

In recent years, a variety of mental diseases have been demonstrated to be linked with air pollution. For example, Song and coworkers studied the acute impacts of ambient particulate matter on hospital visits for mental and behavioral disorders in Shijiazhuang, China, during 2014-2016 utilizing an over-dispersed, generalized additive model. The findings indicated that ambient $PM_{2.5}$ and PM_{10} increased the risk of hospital visits for mental and behavioral disorders, and the effects were higher in male and elderly population (⩾45 years old). In general, the effects were stronger in the cool season than that in the warm season (Song et al. 2018b). Additionally, Chen et al. used over-dispersed, generalized additive models to suggest that PM_{10}, SO_2, and CO were significantly related to the risks of daily admissions for mental disorders in Shanghai, China in 2013-2015, and the effects were more obvious in the warm season (Chen et al. 2018b).

Some studies have revealed that air pollution is associated with some mental diseases. For instance, the significant associations of $PM_{2.5}$, PM_{10} and PM_c in Chengdu, China with increased risk of hospital admissions for overall and specific mental disorders were observed in a generalized additive model; the association was stronger in

Table 2 Air pollution impacts on circulatory system health

Impacts on health	Air pollutants	References
Blood pressure, hypertension	NO_2, $PM_{2.5}$, PM_{10}	Li et al., 2020
Hypertension	$PM_{2.5}$	Liu et al., 2017a
Hypertension, blood pressure	PM_1	Li et al., 2019a
Circulatory emergency department visits	SO_2	Guo et al., 2018b
Cardio-cerebrovascular hospital outpatient visits	$PM_{2.5}$, PM_{10}	Wang et al., 2019a
Cardiovascular hospital admissions	$PM_{2.5}$, SO_2, NO_2	Wang et al., 2018a
Cardiovascular, ischemic heart disease and high blood pressure emergency department visits	$PM_{2.5}$	Ma et al., 2019
Type II diabetes mellitus hospitalization	$PM_{2.5}$, PM_{10}, SO_2, NO_2, CO	Song et al., 2018a
Diabetes mortality	PM_{10}	Yang et al., 2020c
Type II diabetes mellitus hospitalization	$PM_{2.5}$	Liu et al., 2016a
Type II diabetes mellitus	PM_1, $PM_{2.5}$, PM_{10}	Yang et al., 2018
Mortality among children aged < 5 years	SO_2, NO_2	Wang et al., 2019b
Cardiovascular mortality	PM_c	Wang et al., 2018b
Circulatory, hypertensive and respiratory mortality	$PM_{2.5}$, PM_{10}	Yu et al., 2019
Cardiovascular mortality	PM_{10}, SO_2	Zhang et al., 2017
Cardiovascular mortality	O_3	Zhang et al., 2019a

males and in cool periods. Furthermore, PMs significantly contributed to high risks of dementia, schizophrenia and depression (Qiu et al. 2019). Duan et al. observed that NO_2, SO_2 and PM_{10} had a significant relationship with the schizophrenic admissions in Tongling, China from 2014 to 2016 using a distributed lag nonlinear model combined with a Poisson generalized linear regression model. The effect of NO_2 and PM_{10} on schizophrenia was short-term, yet SO_2 showed longer effects. In Particular, males, people aged 20–59 years, farmers and workers were vulnerable to high levels of air pollution (Duan et al. 2018).

PD is one of the most common neurodegenerative diseases. Many studies have revealed the significant associations of air pollution with PD. Lee et al. verified that traffic-related air pollutants (NO_x and CO) could account for the increased risk of PD in Taiwan, China using logistic regression models; this association may be attributed to the harmful influences of traffic-related air pollution on the aging brain. High concentrations of PM_c could increase the risk of PD (Lee et al. 2016).

AD is also a type of neurodegenerative disease that can cause disability in activities of daily living, cognitive impairment, and health deficits. Many reports have revealed that air pollution is positively associated with AD (Shou et al. 2019). In 2010, Zeng et al. found that air pollution increased the odds of disability in activities of daily living, cognitive impairment, and health problems by using multilevel logistic regression models to analyze data from a nationally representative sample of 15,973 elderly residents of 866 counties and cities in China (Zeng et al. 2010). Chen's group has found that the highest levels of PM_{10} or O_3 exposure increased the risk of AD and vascular dementia based on a case-control study in northern Taiwan, China in 2007–2010 using conditional logistic regression models (Wu et al. 2015). In addition, a cohort study of 95,690 individuals aged at $\geqslant$65 years in Taiwan, China in 2001–2010 revealed that a 10.91 ppb increase in O_3 over 10 years caused a 211% increase in the odds of newly diagnosed AD, and exposure to a 4.34 μg/m^3 increase in $PM_{2.5}$ over the follow-up period increased the risk of newly diagnosed AD by 138% (Jung et al. 2015). Importantly, long-term exposure to air pollution has been verified to hinder cognitive performance on verbal and math tests. The effect was more obvious as people age, particularly for men and the less educated, warning us that air pollution exhibited a damaging effect on the aging brain (Zhang et al. 2018).

More seriously, air pollution could induce suicide attempts to some extent. The long-term effects of $PM_{2.5}$ on suicide attempts among Chinese adolescents in Guangdong, China during 2011–2013 were explored using multi-level logistic regression models. The findings suggested that long-term exposure to $PM_{2.5}$ led to increased risks of suicide attempts among adolescents, and $PM_{2.5}$ and sleep disturbances exerted a combined impact on suicide attempts, indicating that fresh air may reduce the risks of suicide attempts among adolescents (Fan et al. 2019).

Eyes are important organs that are directly affected by air pollution. It has been reported that air pollution has been associated with some eye illness, including myopia (Wei et al. 2019a), dry eye (Mo et al. 2019), and conjunctivitis (Fu et al. 2017; Lu et al. 2019a). Wei et al. observed that exposure to ambient $PM_{2.5}$ and NO_x was related to the risk of myopia in Taiwan, China, and animal experiments further confirmed that $PM_{2.5}$ caused inflammation in the eye and triggered myopia in Syrian hamsters (Wei et al. 2019a). Dry eye diseases were found to be significantly related to exposure to air pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, and CO) in Hangzhou, China, on the basis of a time-stratified case-crossover model. Particularly, the strongest relationships were discovered in the cold season and in patients aged 21–40 years (Mo et al. 2019). The associations of air pollution with conjunctivitis outpatient visits in Hangzhou, China were assessed based on a time-stratified case-crossover study design and conditional logistic regression models. A 10 μg/m^3 elevation in PM_{10}, $PM_{2.5}$, SO_2, NO_2, and CO levels contributed to the increased conjunctivitis outpatient visits. SO_2 exerted the strongest effect on patients aged 2–5 years (Fu et al. 2017). Recently, a multi-city study suggested that $PM_{2.5}$, PM_{10}, NO_2, SO_2 and O_3 promoted an increase in the risk of conjunctivitis in China. In particular, the impacts were stronger in the warm season. Female conjunctivitis hospital outpatients were more susceptible to air pollution. Importantly, NO_2 and O_3 exhibited more serious effects on conjunctivitis than PMs and SO_2 due to the acidity of NO_2 and the strong oxidative ability of O_3 (Lu et al. 2019a). Song et al. noticed that short-term exposure to NO_2 could raise the risk of hospital visits for eye and adnexa diseases in Xinxiang, China, based on an over-dispersed generalized additive model. They found that the associations were largest and statistically significant on the current day, and the strongest effects were observed with keratitis (Song et al. 2019). These results suggested that air pollution was associated with eye health, particularly for $PM_{2.5}$, O_3 and NO_x, which is similar to associations observed in South Korea (Kim et al. 2020). Furthermore, we should avoid outdoor activities in polluted days.

The results of this section suggested that air pollution is significantly associated with nervous health including poor sleep quality, sleep disorders, sleeplessness, mental disorders, schizophrenic admissions, Parkinson's disease, suicide attempts and different eye diseases (Table 3), warning us to control air pollution.

3.4 Digestive system

Associations between air pollution and digestive system diseases have also been demonstrated. To date, the effects of air pollution on the health of the digestive system have mainly focused on peptic ulcer bleeding (PUB) and hand-

Table 3 Summary of the effects of air pollution on the health of nervous system.

Impacts on health	Air pollutants	References
Poor sleep quality	NO_2, $PM_{2.5}$	Chen et al., 2019b
Sleep disorders	NO_2, SO_2, O_3, $PM_{2.5}$, PM_{10}	Tang et al., 2019
Sleeplessness	AQI, $PM_{2.5}$	Heyes and Zhu 2019
Hospital visits for mental and behavioral disorders	$PM_{2.5}$ and PM_{10}	Song et al., 2018b
Daily admissions for mental disorders	PM_{10}, SO_2, CO	Chen et al., 2018b
Hospital admissions for overall and specific mental disorders	$PM_{2.5}$, PM_{10}, PM_C	Qiu et al., 2019
Schizophrenic admissions	NO_2, SO_2, PM_{10}	Duan et al., 2018
Parkinson's disease	NO_x, CO, PM_c	Lee et al., 2016
Daily living activities, cognitive impairment, health problems	Air pollution index	Zeng et al., 2010
Alzheimer’s disease, vascular dementia	PM_{10}, O_3	Wu et al., 2015
Alzheimer’s disease	O_3, $PM_{2.5}$	Jung et al., 2015
Cognitive performance on verbal and math tests	Air pollution index	Zhang et al., 2018
Suicide attempts among adolescents	$PM_{2.5}$	Fan et al., 2019
Myopia	$PM_{2.5}$, NO_x	Wei et al., 2019a
Dry eye diseases	PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO	Mo et al., 2019
Conjunctivitis outpatient	PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO	Fu et al., 2017
Conjunctivitis	$PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3	Lu et al., 2019a
Hospital visits for eye and adnexa diseases	NO_2	Song et al., 2019

foot-and-mouth disease (HFMD). In 2017, the impacts of air pollution on emergency admission for PUB in Hong Kong's elderly population were examined based on a time stratified case-crossover analysis with conditional logistic regression. The results indicated that NO_2 was significantly related to PUB emergency admissions (Tian et al. 2017). Additionally, the relationships between short-term exposure to $PM_{2.5}$ and emergency admissions for PUB in Beijing, China, were demonstrated by employing a generalized additive Poisson model. The results indicated that $PM_{2.5}$ significantly contributed to an increase in emergency admissions for PUB, and the impacts were stronger in elderly people (Duan et al. 2019).

HFMD, an acute infectious disease caused by enterovirus mainly occurs in infants and young children. Notably, HFMD can lead to death. Recently, some studies suggested that air pollution was associated with HFMD incidence. Wei et al. first observed that short-term exposure to ambient SO_2 could contribute to an increase in the risk of HFMD in Hefei, China on the basis of a Poisson generalized additive model and the time-series regression analyses. Adverse impacts were found to occur with on lag0, lag1, lag01 and lag02; the cold season strengthened the impacts. Moreover, female and scattered children were more sensitive to SO_2 (Wei et al. 2019b). These results revealed that exposure to ambient air pollution could significantly affect the health of the digestive system, particularly for elderly people and children. The underlying reasons for these relationships should be further explored (Table 4).

Table 4 List of the impacts of air pollution on digestive system health

Impacts on health	Air pollutants	References
Peptic ulcer bleeding	NO_2	Tian et al., 2017
Peptic ulcer bleeding	$PM_{2.5}$	Duan et al., 2019
Hand-foot-and-mouth disease	SO_2	Wei et al., 2019b

3.5 Urinary system

Additionally, air pollution also affects on the health of the urinary system. Studies to date have mainly focused on the impacts of air pollution on kidney function. Wang et al. assessed the associations of air pollution and kidney function among adult women (aged 18-65 years) in Mianyang, China based on multivariable linear regression analyses. They assessed kidney function by measuring serum concentrations of uric acid, urea, creatinine, and cystatin C and calculated the individual estimated glomerular filtration rate (eGFR) using a cystatin C-based equation developed specifically for Chinese patients with the CKD equation. The average daily dose (ADD) of pollutants, based on the basis of the air quality complex index, was employed to estimate the air quality. The authors observed that ADD was positively related to serum concentrations of uric acid, urea, creatinine, and cystatin C, but it was negatively associated with eGFR. In total, the results revealed that air pollution showed deleterious effects on kidney function (Wang et al. 2020a). Additionally, the effects of traffic-related air pollution on chronic kidney disease in the elderly people in Taipei, China were explored using generalized linear regressions and logistic regressions. They found that the interquartile range-elevations of $PM_{2.5}$ absorbance (0.4×10^{-5}/m) and NO_2 (7.0 μg/m^3) accounted for a 1.07% and 0.84% lower eGFR, respectively. The effects were magnified in people with an eGFR>60 mL/min/1.73 m^2 or nondiabetic history. PM_{10} and $PM_{2.5\text{-}10}$ also showed similar impacts (Chen et al. 2018d). These results indicated that air pollution could exhibit adverse effects on the urinary system; thus, strict measures should be taken to reduce air pollution. Moreover, the influence of air pollution on other diseases of the urinary system should be further explored (Table 5).

Table 5 List of the impacts of air pollution on urinary system health

Impacts on health	Air pollutants	References
Kidney function	Individual average daily dose	Wang et al., 2020a
Chronic kidney disease	NO_2, $PM_{2.5}$, $PM_{2.5-10}$, PM_{10}	Chen et al., 2018d

3.6 Pregnancy

In recent years, considerable studies have suggested that air pollution is associated with the pregnancy health. Sex ratio is of significance for sustainable development of our society. In 2015, Lin and his coworkers explored the impacts of air pollution before the conception date on the likelihood of giving birth to girls in Guangzhou, China using logistic regression models. The findings suggested that effective exposure to higher levels of air pollutants approximately one week prior to the conception date contributed to a higher chance of female offspring. Particularly, PM_{10}, SO_2 and NO_2 showed significant impacts (Lin et al. 2015). The results tell us that exposure to air pollution prior to conception could affect the sex ratio of newborns.

Weight is an important indicator of the health of newborns. A recent study showed that air pollution (PM_{10}) significantly elevated the risk of term low birthweight (LBW) but not with preterm LBW in China, in multiple logistic regression models (Lu et al. 2020). Recent results revealed that prenatal air pollution exposure could contribute to the increase of the risk of preterm birth in Wuxi, China, based on logistic and linear regression models. The findings suggested that exposure to PM_{10} and O_3 would decrease gestational age. Women at advanced age with maternal PM_{10} exposure had an increased risk of preterm birth (Han et al. 2018). The association between exposure to NO_2 and preterm birth in Shanghai, China, is based on a land use regression model and logistic regression. The results indicated that NO_2 could elevate the chance of preterm birth, particularly for exposures during the third trimester, the month and the week before delivery (Ji et al. 2019). The relationships between prenatal $PM_{2.5}$ exposure and fetal distress were also demonstrated in Wuhan, China based on a land use regression model, logistic regression model, and generalized estimating equations. They found that a per 10 μg/m^3 change in maternal $PM_{2.5}$ level throughout pregnancy was linked with a 25% increased risk of fetal distress. The potential sensitive window was exposure to $PM_{2.5}$ in the 2nd trimester. The effects were stronger in cold seasons (Liu et al. 2019).

Birth defects are also associated with air pollution. Zhao et al. observed that maternal exposure to $PM_{2.5}$, PM_{10}, O_3 and CO exposure could increase the chances of oral clefts in Wuhan, China, based on multiple logistic regression analyses. Especially in the first trimester of pregnancy, a higher risk of oral cleft was noticed among women who were exposed to $PM_{2.5}$, PM_{10}, O_3 and CO (Zhao et al. 2018). These findings suggested that air pollution generated harmful influences on the health of pregnancy, warning us that pregnant women should avoid exposure to air pollution during pre-pregnancy and pregnancy (Table 6).

Table 6 The effects of air pollution on pregnancy

Impacts on health	Air pollutants	References
Likelihood of female offspring	PM_{10}, SO_2, NO_2	Lin et al., 2015
Term low birthweight	PM_{10}	Lu et al., 2020
Preterm birth	PM_{10}, O_3	Han et al., 2018
Preterm birth	NO_2	Ji et al., 2019
Fetal distress	$PM_{2.5}$	Liu et al., 2019
Oral clefts	$PM_{2.5}$, PM_{10}, O_3, CO	Zhao et al., 2018

3.7 Life expectancy

Everyone wants to live a long life. However, life expectancy is associated with many external and internal factors. Clean air is of considerable significance for extending life expectancy. However, polluted air has markedly affected our life expectancy.

He et al. evaluated the relationships between ambient air pollution and years of life lost (YLL) in Ningbo, China by using a time series analysis of the data on air pollution, meteorological conditions and 163,704 non-accidental deaths from 2009 to 2013. They found that an 10 μg/m^3 increase in PM_{10}, $PM_{2.5}$, SO_2 and NO_2 corresponded to an increase of 4.27, 2.97, 29.98 and 16.58 YLL, respectively, and 0.53%, 0.57%, 2.89%, and 1.65% increases in daily death counts, respectively. The effects were stronger in the elderly population (He et al. 2016). The impacts of air pollution on YLL and mortality in Wuxi, China have been assessed based on a time-series analysis of air pollutants, meteorological variables and daily data relative to YLL and death counts in 2012-2015 by using linear and Poisson regression models and controlling for time-varying factors.

The results indicated that an interquartile range increase in three-day average cumulative (lag 0–2 days) concentrations of $PM_{2.5}$, PM_{10}, NO_2 and SO_2 was associated with increases of 12.09, 13.69, 26.95 and 24.39 YLL, respectively, and with mortality increases of 1.34%, 1.56%, 3.36% and 2.39%, respectively. Specifically, death from cardiovascular and respiratory diseases was positively associated with NO_2 and SO_2, and the death from diabetes was positively associated with NO_2. The effects were found to be more evident in the cool season than in the warm season. The elderly population (>65 years) and females were more sensitive to air pollution (Zhu et al. 2017). Ebenstein et al. found that a 10-μg/m^3 increase in PM_{10} could lead to a loss of 0.64 years in the life expectancy of Chinese people based on the analysis of China’s Huai River Policy (Ebenstein et al. 2017). Moreover, the associations between $PM_{2.5}$ and adult life expectancy in Taiwan, China were examined by using linear regression to analyze the data of county-level $PM_{2.5}$ and adult life expectancy in 2010–2017. The results revealed that people in counties with higher levels of $PM_{2.5}$ suffered from reduced life expectancy. A 10 μg/m^3 increase in $PM_{2.5}$ contributed to a 0.3-year decrease in adult life expectancy (Chen et al. 2019a). The results demonstrated that our life expectancy is closely related to air pollution. These abovementioned results indicated that our life expectancy has been threatened by air pollution (Table 7). Comfortingly, the Chinese government has strictly implemented the Air Pollution Prevention and Control Action Plan to control air pollution, and considerable achievements have been made. For example, the annual average $PM_{2.5}$ concentrations in China’s mainland decreased by 39.5% from 2013 to 2017, resulting in a 12.6% reduction in premature deaths attributable to $PM_{2.5}$ (Zou et al. 2019).

The above-mentioned results revealed that exposure to ambient air pollution could significantly affect the health of the respiratory diseases, the circulatory system, the nervous system, the digestive system, the urinary system, pregnancy and life expectancy. We should take effective measures to avoid and control air pollution.

4 Actions to control air pollution in China

These findings suggested that exposure to ambient air pollution was significantly linked to a variety of human diseases, including the respiratory system, the circulatory system, the nervous system, the digestive system, the urinary system, pregnancy and life expectancy. In recent years, the Chinese government and people have realized the seriousness and harm of air pollution. A number of measures have been issued to reduce air pollution.

The Chinese government has implemented a series of policies. Chinese Ambient Air Quality Standards (GB3095-2012) were issued in 2012, and enforced in 2016 to protect and improve the environment of China. In 2013, the Chinese government released the well-known Air Pollution Prevention and Control Action Plan, which is the first national policy to control air pollution. In the policy, general requirements, goals, specific targets, key actions and concrete measures to alleviate air pollution have been issued. Recent studies have suggested that the overall air quality has been improved greatly, yet air pollution has not been alleviated in some regions. The levels of $PM_{2.5}$, NO_x and O_3 need to be further controlled (Feng et al. 2019; Huang et al. 2018). Reductions in emissions of air pollutants and CO_2 in the Jing-Jin-Ji region were benefits of this action plan (Lu et al. 2019b). Xue et al. examined changes in $PM_{2.5}$ exposure and the associated health effects in China in 2013-2017 by utilizing an optimal estimator of $PM_{2.5}$ combining in situ observations, satellite measurements, and simulations from a chemical transport model. The premature deaths due to $PM_{2.5}$ exposure were also evaluated by using well-developed exposure-response functions. The national population-weighed annual mean $PM_{2.5}$ concentrations were found to be reduced from 67.4 μg/m^3 in 2013 to 45.5 μg/m^3 in 2017 (32% reduction), which resulted in a 14% decrease in premature deaths due to long-term exposure to $PM_{2.5}$. Additionally, the rapid reduction in the number of heavily polluted days has brought about a 61% reduction in the deaths associated with acute exposure (Xue et al. 2019). Moreover, the health effects of the policy to control air pollution were assessed by analyzing national air quality monitoring and mortality data in 74 key cities in China between 2013 and 2017. The findings indicated that the annual average concentrations of $PM_{2.5}$, PM_{10}, SO_2 and CO in 74 key cities dropped by 33.3%, 27.8%, 54.1% and 28.2%, respectively, during the 5-year period, while the annual average concentration of NO_2 remained no obvious change and the annual average concentration of O_3 increased by 20.4%. Benefiting from the substantial improvements in air quality, there were 47,240 fewer deaths and 710,020 fewer years of life lost in the 74 key cities in 2017 than in 2013 (Huang et al. 2018). A hybrid remote sensing-geostatistical method and the exposure factor-enhanced IER model were used to evaluate the health impacts of $PM_{2.5}$ at 1 km spatial resolution across China’s mainland from 2013 to 2017. They observed that the $PM_{2.5}$ levels declined by 39.5% during the study time period, and the associated premature deaths due to $PM_{2.5}$ decreased by 12.6% (Zou et al. 2019). The results indicated that the Air Pollution Prevention and Control Action Plan of China has greatly improved air quality and alleviated the health impacts of air pollution.

Furthermore, the local governments in China have also issued concrete policies to control air pollution, which also played important roles in the reduction of air pollution. For instance, China's provincial emission reduction policies could cut down PM_{10} emissions and the provincial renewable energy policies decreased emissions of $PM_{2.5}$

and SO_2 (Zeng et al. 2019a). Renewable energy technological innovation could also significantly alleviated China's emissions of NO_x and PM_{10} (Zhu et al. 2020).

Importantly, the local air pollution control policies have also brought about air quality improvement, health benefits and economic benefits. Specifically, the environmental, health and economic co-benefits due to local air pollution control policies have been estimated in Jinan, China, in the 2013–2017 period. They found that annual reductions in SO_2, $PM_{2.5}$ and PM_{10} were 72.6%, 43.1% and 34.2%, respectively. A total of 15,822 related morbidity cases and 2,317 premature deaths were avoided in 2017, saving a total of US$ 317.7 million. If the $PM_{2.5}$ concentration was decreased to 15 μg/m^3, the total $PM_{2.5}$-related nonaccidental mortality and $PM_{2.5}$-related morbidity would decline by 70% and 95%, respectively, avoiding approximately US$ 1,289.5 million financial losses (Cui et al. 2020). Compared to 2004–2009, the annual average concentrations of PM_{10} and SO_2 in Lanzhou, China have declined by 19.28% and 66.29%, respectively, and the mortality risk attributable to PM_{10} dropped significantly (Liu et al. 2020). At the same time, the average life expectancy of urban residents extended from 78.53 to 79.86 years (Wu et al. 2020). These results reveal that local air quality in China has been improved since the implementation of air pollution controlling policies.

Moreover, China's government should put considerable efforts into increasing green spaces to reduce air pollutant concentrations because green plants can contribute to reduced of air pollutant levels (Wang et al. 2020b). To effectively reduce air pollution, China's government, companies and individuals should strictly comply with the air pollution control policies to alleviate air pollution.

Table 7 The effects of air pollution on life expectancy

Impacts on health	Air pollutants	References
Years of life lost	$PM_{2.5}$, PM_{10}, SO_2, NO_2	He et al., 2016
Years of life lost, mortality	$PM_{2.5}$, PM_{10}, NO_2, SO_2	Zhu et al., 2017
Life expectancy	PM_{10}	Ebenstein et al., 2017
Adult life expectancy	$PM_{2.5}$	Chen et al., 2019a

5 Conclusions

In conclusion, we have summarized the health impacts of air pollution in China. Studies have exhibited that air pollution could affect the health conditions of the respiratory system, the circulatory system, the nervous system, the digestive system, the urinary system, pregnancy and life expectancy. To reduce the harmful effects on human health, Chinese governments have released strict air pollution control policies. Recent findings have suggested that these measures have greatly decreased air pollutant levels. However, challenges still remain. First, the associations of air pollution with other diseases should be further explored, such as some chronic diseases, fatal diseases, and infectious diseases. The molecular mechanisms of how these diseases are affected by air pollution should be demonstrated in detail, which may require many interdisciplinary studies with experts from different fields. Second, the long-term impacts of air pollution on human health should be examined; these impacts may be useful to elaborate the intrinsic relationships between air pollution and human health. Third, China's governments should further issue more concrete policies to cut down air pollution. The governments, companies and individuals in China also strictly comply with these policies. Fourth, the impacts of O_3 on human health should be studied in-depth due to the gradual elevation of O_3 levels in China. The synergistic effects of O_3 and other air pollutants on health needs further study. Fifth, the Chinese ambient air quality standards should be revised in light of the health effects of different air pollutants. The safety threshold of different air pollutants in different places should be specified. Moreover, research on technological innovation to reduce or eliminate air pollution needs to be further studied. For example, the utilization of renewable or clean energy should be expanded. Traditional technologies or processes with high energy consumption or high pollution need to be further optimized. Only in this way, can the effects of air pollution on health in China be cut down to the minimum or eliminated and the goals of sustainable economic and social development in China be achieved.

Acknowledgements The authors acknowledge the financial support received from the Foundation of NUIST-UoR International Research Institute, and the Start-up Foundation for Introducing Talent of NUIST (2018r056).

References

Boudier H A J S, Lenoble J L M L, Messing M W J, Huijberts M S P, Lenoble F A C, Vanessen H (1992). The microcirculation and hypertension. Journal of Hypertension, 10: S147–S156

Buist A S, McBurnie M A, Vollmer W M, Gillespie S, Burney P, Mannino D M, Menezes A M B, Sullivan S D, Lee T A, Weiss K B, Jensen R L, Marks G B, Gulsvik A, Nizankowska-Mogilnicka E (2007). International variation in the prevalence of COPD (The BOLD Study): A population-based prevalence study. Lancet, 370 (9589): 741–750

Chai G, He H, Sha Y, Zhai G, Zong S (2019). Effect of $PM_{2.5}$ on daily outpatient visits for respiratory diseases in Lanzhou, China. Science of the Total Environment, 649: 1563–1572

Chang Y K, Wu C C, Lee L T, Lin R S, Yu Y H, Chen Y C (2012). The short-term effects of air pollution on adolescent lung function in Taiwan. Chemosphere, 87(1): 26–30

Chen C, Li C, Li Y, Liu J, Meng C, Han J, Zhang Y, Xu D (2018a).

Short-term effects of ambient air pollution exposure on lung function: A longitudinal study among healthy primary school children in China. Science of the Total Environment, 645: 1014–1020

Chen C, Liu C, Chen R, Wang W, Li W, Kan H, Fu C (2018b). Ambient air pollution and daily hospital admissions for mental disorders in Shanghai, China. Science of the Total Environment, 613–614: 324–330

Chen C C, Chen P S, Yang C Y (2019a). Relationship between fine particulate air pollution exposure and human adult life expectancy in Taiwan. Journal of Toxicology and Environmental Health. Part A., 82 (14): 826–832

Chen G, Xiang H, Mao Z, Huo W, Guo Y, Wang C, Li S (2019b). Is long-term exposure to air pollution associated with poor sleep quality in rural China? Environment International, 133: 105205

Chen G, Zhang W, Li S, Williams G, Liu C, Morgan G G, Jaakkola J J K, Guo Y (2017a). Is short-term exposure to ambient fine particles associated with measles incidence in China? A multi-city study. Environmental Research, 156: 306–311

Chen G, Zhang Y, Zhang W, Li S, Williams G, Marks G B, Jalaludin B, Abramson M J, Luo F, Yang D, Su X, Lin Q, Liu L, Lin J, Guo Y (2017b). Attributable risks of emergency hospital visits due to air pollutants in China: A multi-city study. Environmental Pollution, 228: 43–49

Chen L, Hu G, Fan R, Lv Y, Dai Y, Xu Z (2018c). Association of PAHs and BTEX exposure with lung function and respiratory symptoms among a nonoccupational population near the coal chemical industry in Northern China. Environment International, 120: 480–488

Chen S Y, Chu D C, Lee J H, Yang Y R, Chan C C (2018d). Traffic-related air pollution associated with chronic kidney disease among elderly residents in Taipei City. Environmental Pollution, 234: 838–845

Cui L, Zhou J, Peng X, Ruan S, Zhang Y (2020). Analyses of air pollution control measures and co-benefits in the heavily air-polluted Jinan city of China, 2013–2017. Scientific Reports, 10(1): 5423

Duan J, Cheng Q, Luo X, Bai L, Zhang H, Wang S, Xu Z, Gao J, Zhang Y, Su H (2018). Is the serious ambient air pollution associated with increased admissions for schizophrenia? Science of the Total Environment, 644: 14–19

Duan R R, Hao K, Yang T (2020). Air pollution and chronic obstructive pulmonary disease. Chronic Diseases and Translational Medicine, online doi:10.1016/j.cdtm.2020.05.004

Duan R, Tian Y, Hu Y, Duan L (2019). Exploring the association between short-term exposure to ambient fine particulate matter pollution and emergency admissions for peptic ulcer bleeding in Beijing, China. Atmospheric Environment, 213: 485–490

Ebenstein A, Fan M, Greenstone M, He G, Zhou M (2017). New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy. Proceedings of the National Academy of Sciences of the United States of America, 114 (39): 10384–10389

Fan B, Wang T, Wang W, Zhang S, Gong M, Li W, Lu C, Guo L (2019). Long-term exposure to ambient fine particulate pollution, sleep disturbance and their interaction effects on suicide attempts among Chinese adolescents. Journal of Affective Disorders, 258: 89–95

Fan H, Zhao C, Yang Y (2020a). A comprehensive analysis of the spatio-temporal variation of urban air pollution in China during 2014–2018. Atmospheric Environment, 220: 117066

Fan Y, Ding X, Hang J, Ge J (2020b). Characteristics of urban air pollution in different regions of China between 2015 and 2019. Building and Environment, 180: 107048

Feng Y, Ning M, Lei Y, Sun Y, Liu W, Wang J (2019). Defending blue sky in China: Effectiveness of the "Air Pollution Prevention and Control Action Plan" on air quality improvements from 2013 to 2017. Journal of Environmental Management, 252: 109603

Fu Q, Mo Z, Lyu D, Zhang L, Qin Z, Tang Q, Yin H, Xu P, Wu L, Lou X, Chen Z, Yao K (2017). Air pollution and outpatient visits for conjunctivitis: A case-crossover study in Hangzhou, China. Environmental Pollution, 231: 1344–1350

Gao N, Xu W, Ji J, Yang Y, Wang S T, Wang J, Chen X, Meng S, Tian X, Xu K F (2020). Lung function and systemic inflammation associated with short-term air pollution exposure in chronic obstructive pulmonary disease patients in Beijing, China. Environmental Health, 19(1): 12

Gao Y, Chan E Y, Li L, Lau P W, Wong T W (2014). Chronic effects of ambient air pollution on respiratory morbidities among Chinese children: A cross-sectional study in Hong Kong. BMC Public Health, 14(1): 105

Gao Y, Chan E Y, Li L P, He Q Q, Wong T W (2013). Chronic effects of ambient air pollution on lung function among Chinese children. Archives of Disease in Childhood, 98(2): 128–135

González-Díaz S N, Arias-Cruz A, Macouzet-Sánchez C, Partida-Ortega A B (2016). Impact of air pollution in respiratory allergic diseases. Medicina Universitaria, 18(73): 212–215

Guan W J, Zheng X Y, Chung K F, Zhong N S (2016). Impact of air pollution on the burden of chronic respiratory diseases in China: time for urgent action. Lancet, 388(10054): 1939–1951

Guo C, Zhang Z, Lau A K H, Lin C Q, Chuang Y C, Chan J, Jiang W K, Tam T, Yeoh E K, Chan T C, Chang L Y, Lao X Q (2018a). Effect of long-term exposure to fine particulate matter on lung function decline and risk of chronic obstructive pulmonary disease in Taiwan: A longitudinal, cohort study. Lancet. Planetary Health, 2(3): e114–e125

Guo P, Feng W, Zheng M, Lv J, Wang L, Liu J, Zhang Y, Luo G, Zhang Y, Deng C, Shi T, Liu P, Zhang L (2018b). Short-term associations of ambient air pollution and cause-specific emergency department visits in Guangzhou, China. Science of the Total Environment, 613–614: 306–313

Han Y, Jiang P, Dong T, Ding X, Chen T, Villanger G D, Aase H, Huang L, Xia Y (2018). Maternal air pollution exposure and preterm birth in Wuxi, China: Effect modification by maternal age. Ecotoxicology and Environmental Safety, 157: 457–462

He T, Yang Z, Liu T, Shen Y, Fu X, Qian X, Zhang Y, Wang Y, Xu Z, Zhu S, Mao C, Xu G, Tang J (2016). Ambient air pollution and years of life lost in Ningbo, China. Scientific Reports, 6(1): 22485

Heyes A, Zhu M (2019). Air pollution as a cause of sleeplessness: Social media evidence from a panel of Chinese cities. Journal of Environmental Economics and Management, 98: 102247

Hou D, Ge Y, Chen C, Tan Q, Chen R, Yang Y, Li L, Wang J, Ye M, Li C, Meng X, Kan H, Cai J, Song Y (2020). Associations of long-term exposure to ambient fine particulate matter and nitrogen dioxide with lung function: A cross-sectional study in China. Environment International, 144: 105977

Huang J, Pan X, Guo X, Li G (2018). Health impact of China's Air Pollution Prevention and Control Action Plan: an analysis of national air quality monitoring and mortality data. Lancet. Planetary Health, 2 (7): e313–e323

Ji X, Meng X, Liu C, Chen R, Ge Y, Kan L, Fu Q, Li W, Tse L A, Kan H (2019). Nitrogen dioxide air pollution and preterm birth in Shanghai, China. Environmental Research, 169: 79–85

Jin Y, Andersson H, Zhang S (2016). Air Pollution Control Policies in China: A Retrospective and Prospects. International Journal of Environmental Research and Public Health, 13(12): 1219

Jung C R, Lin Y T, Hwang B F (2015). Ozone, particulate matter, and newly diagnosed Alzheimer's Disease: A population-based cohort study in Taiwan. Journal of Alzheimer's Disease, 44(2): 573–584

Karimi B, shokrinezhad B, Samadi S (2019). Mortality and hospitalizations due to cardiovascular and respiratory diseases associated with air pollution in Iran: A systematic review and meta-analysis. Atmospheric Environment, 198: 438–447

Kim Y, Choi Y H, Kim M K, Paik H J, Kim D H (2020). Different adverse effects of air pollutants on dry eye disease: Ozone, $PM_{2.5}$, and PM_{10}. Environmental Pollution, 265: 115039

Kuang H, Liu J, Zeng Y, Zhou W, Wu P, Tan J, Li Y, Pang Q, Jiang W, Fan R (2020). Co-exposure to polycyclic aromatic hydrocarbons, benzene and toluene may impair lung function by increasing oxidative damage and airway inflammation in asthmatic children. Environmental Pollution, 266: 115220

Kumar P, Druckman A, Gallagher J, Gatersleben B, Allison S, Eisenman T S, Hoang U, Hama S, Tiwari A, Sharma A, Abhijith K V, Adlakha D, McNabola A, Astell-Burt T, Feng X, Skeldon A C, de Lusignan S, Morawska L (2019). The nexus between air pollution, green infrastructure and human health. Environment International, 133: 105181

Lee P C, Liu L L, Sun Y, Chen Y A, Liu C C, Li C Y, Yu H L, Ritz B (2016). Traffic-related air pollution increased the risk of Parkinson's disease in Taiwan: A nationwide study. Environment International, 96: 75–81

Levy B I, Ambrosio G, Pries A R, Struijker-Boudier H A(2001). Microcirculation in hypertension: A new target for treatment? Circulation, 104(6): 735–740

Li N, Chen G, Liu F, Mao S, Liu Y, Hou Y, Lu Y, Liu S, Wang C, Xiang H, Guo Y, Li S (2019a). Associations of long-term exposure to ambient PM_1 with hypertension and blood pressure in rural Chinese population: The Henan rural cohort study. Environment International, 128: 95–102

Li N, Chen G, Liu F, Mao S, Liu Y, Liu S, Mao Z, Lu Y, Wang C, Guo Y, Xiang H, Li S (2020). Associations between long-term exposure to air pollution and blood pressure and effect modifications by behavioral factors. Environmental Research, 182: 109109

Li Y R, Xiao C C, Li J, Tang J, Geng X Y, Cui L J, Zhai J X (2018). Association between air pollution and upper respiratory tract infection in hospital outpatients aged 0–14 years in Hefei, China: A time series study. Public Health, 156: 92–100

Li Z, Mao X, Liu Q, Song H, Ji Y, Xu D, Qiu B, Tian D, Wang J (2019b). Long-term effect of exposure to ambient air pollution on the risk of active tuberculosis. International Journal of Infectious Diseases, 87: 177–184

Lin H, Liang Z, Liu T, Di Q, Qian Z, Zeng W, Xiao J, Li X, Guo L, Ma W, Zhao Q (2015). Association between exposure to ambient air pollution before conception date and likelihood of giving birth to girls in Guangzhou, China. Atmospheric Environment, 122: 622–627

Lin H, Wang X, Liu T, Li X, Xiao J, Zeng W, Ma W (2017). Air Pollution and Mortality in China. Advances in Experimental Medicine and Biology, 1017: 103–121

Liu C, Chen R, Zhao Y, Ma Z, Bi J, Liu Y, Meng X, Wang Y, Chen X, Li W, Kan H (2017a). Associations between ambient fine particulate air pollution and hypertension: A nationwide cross-sectional study in China. Science of the Total Environment, 584–585: 869–874

Liu C, Yang C, Zhao Y, Ma Z, Bi J, Liu Y, Meng X, Wang Y, Cai J, Kan H, Chen R (2016a). Associations between long-term exposure to ambient particulate air pollution and type 2 diabetes prevalence, blood glucose and glycosylated hemoglobin levels in China. Environment International, 92–93: 416–421

Liu H, Liao J, Jiang Y, Zhang B, Yu H, Kang J, Hu C, Li Y, Xu S (2019). Maternal exposure to fine particulate matter and the risk of fetal distress. Ecotoxicology and Environmental Safety, 170: 253–258

Liu J, Ruan Y, Wu Q, Ma Y, He X, Li L, Li S, Niu J, Luo B (2020). Has the mortality risk declined after the improvement of air quality in an ex-heavily polluted Chinese city-Lanzhou? Chemosphere, 242: 125196

Liu S, Zhou Y, Liu S, Chen X, Zou W, Zhao D, Li X, Pu J, Huang L, Chen J, Li B, Liu S, Ran P (2017b). Association between exposure to ambient particulate matter and chronic obstructive pulmonary disease: results from a cross-sectional study in China. Thorax, 72 (9): 788–795

Liu W, Huang C, Hu Y, Fu Q, Zou Z, Sun C, Shen L, Wang X, Cai J, Pan J, Huang Y, Chang J, Sun Y, Sundell J (2016b). Associations of gestational and early life exposures to ambient air pollution with childhood respiratory diseases in Shanghai, China: A retrospective cohort study. Environment International, 92–93: 284–293

Liu W, Xu Z, Yang T (2018). Health effects of air pollution in China. International Journal of Environmental Research and Public Health, 15: 1471

Liu Y, Xie S, Yu Q, Huo X, Ming X, Wang J, Zhou Y, Peng Z, Zhang H, Cui X, Xiang H, Huang X, Zhou T, Chen W, Shi T (2017c). Short-term effects of ambient air pollution on pediatric outpatient visits for respiratory diseases in Yichang city, China. Environmental Pollution, 227: 116–124

Louwies T, Nawrot T, Cox B, Dons E, Penders J, Provost E, Panis L I, De Boever P (2015). Blood pressure changes in association with black carbon exposure in a panel of healthy adults are independent of retinal microcirculation. Environment International, 75: 81–86

Lu C, Zhang W, Zheng X, Sun J, Chen L, Deng Q (2020). Combined effects of ambient air pollution and home environmental factors on low birth weight. Chemosphere, 240: 124836

Lu P, Zhang Y, Xia G, Zhang W, Li S, Guo Y (2019a). Short-term exposure to air pollution and conjunctivitis outpatient visits: A multi-city study in China. Environmental Pollution, 254: 113030

Lu Z, Huang L, Liu J, Zhou Y, Chen M, Hu J (2019b). Carbon dioxide mitigation co-benefit analysis of energy-related measures in the Air Pollution Prevention and Control Action Plan in the Jing-Jin-Ji region of China. Resources, Conservation & Recycling: X 1: 100006

Ma W L, Zhu F J, Liu L Y, Jia H L, Yang M, Li Y F (2020). PAHs in Chinese atmosphere Part II: Health risk assessment. Ecotoxicology and Environmental Safety, 200: 110774

Ma Y, Yang S, Yu Z, Jiao H, Zhang Y, Ma B (2019). A study on the short-term impact of fine particulate matter pollution on the incidence of cardiovascular diseases in Beijing, China. Atmospheric Environment, 215: 116889

Miao Z, Baležentis T, Shao S, Chang D (2019). Energy use, industrial soot and vehicle exhaust pollution-China's regional air pollution recognition, performance decomposition and governance. Energy Economics, 83: 501–514

Miller M R (2020). Oxidative stress and the cardiovascular effects of air pollution. Free Radical Biology and Medicine, 151: 69–87

Mo Z, Fu Q, Lyu D, Zhang L, Qin Z, Tang Q, Yin H, Xu P, Wu L, Wang X, Lou X, Chen Z, Yao K (2019). Impacts of air pollution on dry eye disease among residents in Hangzhou, China: A case-crossover study. Environmental Pollution, 246: 183–189

Niu Y, Chen R, Kan H (2017). Air pollution, disease burden, and health economic loss in China. Advances in Experimental Medicine and Biology, 1017: 233–242

Phosri A, Ueda K, Phung V L H, Tawatsupa B, Honda A, Takano H (2019). Effects of ambient air pollution on daily hospital admissions for respiratory and cardiovascular diseases in Bangkok, Thailand. Science of the Total Environment, 651: 1144–1153

Popovic I, Soares Magalhaes R J, Ge E, Marks G B, Dong G H, Wei X, Knibbs L D (2019). A systematic literature review and critical appraisal of epidemiological studies on outdoor air pollution and tuberculosis outcomes. Environmental Research, 170: 33–45

Qiu H, Zhu X, Wang L, Pan J, Pu X, Zeng X, Zhang L, Peng Z, Zhou L (2019). Attributable risk of hospital admissions for overall and specific mental disorders due to particulate matter pollution: A time-series study in Chengdu, China. Environmental Research, 170: 230–237

Ruan Z, Qian Z, Guo Y, Zhou J, Yang Y, Acharya B K, Guo S, Zheng Y, Cummings-Vaughn L A, Rigdon S E, Vaughn M G, Chen X, Wu F, Lin H (2019). Ambient fine particulate matter and ozone higher than certain thresholds associated with myopia in the elderly aged 50 years and above. Environmental Research, 177: 108581

Sáenz-de-Miera O, Rosselló J (2013). Tropospheric ozone, air pollution and tourism: a case study of Mallorca. Journal of Sustainable Tourism, 21(8): 1232–1243

Shou Y, Huang Y, Zhu X, Liu C, Hu Y, Wang H (2019). A review of the possible associations between ambient $PM_{2.5}$ exposures and the development of Alzheimer's disease. Ecotoxicology and Environmental Safety, 174: 344–352

Song C, Wu L, Xie Y, He J, Chen X, Wang T, Lin Y, Jin T, Wang A, Liu Y, Dai Q, Liu B, Wang Y, Mao H (2017). Air pollution in China: Status and spatiotemporal variations. Environmental Pollution, 227: 334–347

Song J, Liu Y, Lu M, An Z, Lu J, Chao L, Zheng L, Li J, Yao S, Wu W, Xu D (2019). Short-term exposure to nitrogen dioxide pollution and the risk of eye and adnexa diseases in Xinxiang, China. Atmospheric Environment, 218: 117001

Song J, Liu Y, Zheng L, Gui L, Zhao X, Xu D, Wu W (2018a). Acute effects of air pollution on type II diabetes mellitus hospitalization in Shijiazhuang, China. Environmental Science and Pollution Research International, 25(30): 30151–30159

Song J, Zheng L, Lu M, Gui L, Xu D, Wu W, Liu Y (2018b). Acute effects of ambient particulate matter pollution on hospital admissions for mental and behavioral disorders: A time-series study in Shijiazhuang, China. Science of the Total Environment, 636: 205–211

Sun S, Tian L, Cao W, Lai P C, Wong P P Y, Lee R S y, Mason T G, Krämer A, Wong C M (2019). Urban climate modified short-term association of air pollution with pneumonia mortality in Hong Kong. Science of the Total Environment, 646: 618–624

Tang M, Li D, Liew Z, Wei F, Wang J, Jin M, Chen K, Ritz B (2019). The association of short-term effects of air pollution and sleep disorders among elderly residents in China. Science of the Total Environment, 708: 134846

Tao Y, Mi S, Zhou S, Wang S, Xie X (2014). Air pollution and hospital admissions for respiratory diseases in Lanzhou, China. Environmental Pollution, 185: 196–201

Tian L, Qiu H, Sun S, Tsang H, Chan K P, Leung W K (2017). Association between emergency admission for peptic ulcer bleeding and air pollution: A case-crossover analysis in Hong Kong's elderly population. Lancet. Planetary Health, 1(2): e74–e81

Wang C, Feng L, Chen K (2019a). The impact of ambient particulate matter on hospital outpatient visits for respiratory and circulatory system disease in an urban Chinese population. Science of the Total Environment, 666: 672–679

Wang H H, Zhang S C, Wang J, Chen X, Yin H, Huang D Y (2020a). Combined toxicity of outdoor air pollution on kidney function among adult women in Mianyang City, southwest China. Chemosphere, 238: 124603

Wang J, Cao H, Sun D, Qi Z, Guo C, Peng W, Sun Y, Xie Y, Liu X, Li B, Luo Y, Pan Y, Li Y, Zhang L (2019b). Associations between ambient air pollution and mortality from all causes, pneumonia, and congenital heart diseases among children aged under 5 years in Beijing, China: A population-based time series study. Environmental Research, 176: 108531

Wang N, Mengersen K, Tong S, Kimlin M, Zhou M, Wang L, Yin P, Xu Z, Cheng J, Zhang Y, Hu W (2019c). Short-term association between ambient air pollution and lung cancer mortality. Environmental Research, 179: 108748

Wang R, Yang B, Yao Y, Bloom M S, Feng Z, Yuan Y, Zhang J, Liu P, Wu W, Lu Y, Baranyi G, Wu R, Liu Y, Dong G (2019d). Residential greenness, air pollution and psychological well-being among urban residents in Guangzhou, China. Science of the Total Environment, 711: 134843

Wang R, Yang B, Yao Y, Bloom M S, Feng Z, Yuan Y, Zhang J, Liu P, Wu W, Lu Y, Baranyi G, Wu R, Liu Y, Dong G (2020b). Residential greenness, air pollution and psychological well-being among urban residents in Guangzhou, China. Science of the Total Environment, 711: 134843

Wang X, Wang W, Jiao S, Yuan J, Hu C, Wang L (2018a). The effects of air pollution on daily cardiovascular diseases hospital admissions in Wuhan from 2013 to 2015. Atmospheric Environment, 182: 307–312

Wang X, Zhang L, Yao Z, Ai S, Qian Z, Wang H, BeLue R, Liu T, Xiao J, Li X, Zeng W, Ma W, Lin H (2018b). Ambient coarse particulate pollution and mortality in three Chinese cities: Association and attributable mortality burden. Science of the Total Environment, 628–629: 1037–1042

Wei C C, Lin H J, Lim Y P, Chen C S, Chang C Y, Lin C J, Chen J J Y, Tien P T, Lin C L, Wan L (2019a). $PM_{2.5}$ and NO_x exposure promote myopia: Clinical evidence and experimental proof. Environmental Pollution, 254: 113031

Wei Q, Wu J, Zhang Y, Cheng Q, Bai L, Duan J, Gao J, Xu Z, Yi W, Pan R, Su H (2019b). Short-term exposure to sulfur dioxide and the risk of childhood hand, foot, and mouth disease during different seasons in Hefei, China. Science of the Total Environment, 658: 116–121

Wu Y, Wang W, Liu C, Chen R, Kan H (2020). The association between long-term fine particulate air pollution and life expectancy in China, 2013 to 2017. Science of the Total Environment, 712: 136507

Wu Y C, Lin Y C, Yu H L, Chen J H, Chen T F, Sun Y, Wen L L, Yip P K, Chu Y M, Chen Y C (2015). Association between air pollutants and dementia risk in the elderly. Alzheimer's & Dementia: Diagnosis, Assessment & Disease Monitoring, 1(2): 220–228

Xia Y, Liu X, Wu D, Xiong H, Ren L, Xu L, Wu W, Zhang H (2017). Influence of beat-to-beat blood pressure variability on vascular elasticity in hypertensive population. Scientific Reports, 7(1): 8394

Xue T, Liu J, Zhang Q, Geng G, Zheng Y, Tong D, Liu Z, Guan D, Bo Y, Zhu T, He K, Hao J (2019). Rapid improvement of $PM_{2.5}$ pollution and associated health benefits in China during 2013–2017. Science China. Earth Sciences, 62(12): 1847–1856

Yan D, Wu S, Zhou S, Tong G, Li F, Wang Y, Li B (2019). Characteristics, sources and health risk assessment of airborne particulate PAHs in Chinese cities: A review. Environmental Pollution, 248: 804–814

Yang B Y, Fan S, Thiering E, Seissler J, Nowak D, Dong G H, Heinrich J (2020a). Ambient air pollution and diabetes: A systematic review and meta-analysis. Environmental Research, 180: 108817

Yang B Y, Qian Z, Li S, Chen G, Bloom M S, Elliott M, Syberg K W, Heinrich J, Markevych I, Wang S Q, Chen D, Ma H, Chen D H, Liu Y, Komppula M, Leskinen A, Liu K K, Zeng X W, Hu L W, Guo Y, Dong G H (2018). Ambient air pollution in relation to diabetes and glucose-homoeostasis markers in China: A cross-sectional study with findings from the 33 Communities Chinese Health Study. Lancet. Planetary Health, 2(2): e64–e73

Yang J, Kang S, Ji Z, Yin X, Tripathee L (2020b). Investigating air pollutant concentrations, impact factors, and emission control strategies in western China by using a regional climate-chemistry model. Chemosphere, 246: 125767

Yang J, Zhou M, Zhang F, Yin P, Wang B, Guo Y, Tong S, Wang H, Zhang C, Sun Q, Song X, Liu Q (2020c). Diabetes mortality burden attributable to short-term effect of PM_{10} in China. Environmental Science and Pollution Research International, 27(15): 18784–18792

Yu F, Ma G, Zhang Y, Cao D, Gao F, Jinnan W (2013). Review on studies of environmental impact on health from air pollution in China. National Medical Journal of China, 93: 2695–2698

Yu Y, Yao S, Dong H, Wang L, Wang C, Ji X, Ji M, Yao X, Zhang Z (2019). Association between short-term exposure to particulate matter air pollution and cause-specific mortality in Changzhou, China. Environmental Research, 170: 7–15

Zeng J, Liu T, Feiock R, Li F (2019a). The impacts of China's provincial energy policies on major air pollutants: A spatial econometric analysis. Energy Policy, 132: 392–403

Zeng X W, Vivian E, Mohammed K A., Jakhar S, Vaughn M, Huang J, Zelicoff A, Xaverius P, Bai Z, Lin S, Hao Y T, Paul G, Morawska L, Wang S Q, Qian Z, Dong G H (2016). Long-term ambient air pollution and lung function impairment in Chinese children from a high air pollution range area: The Seven Northeastern Cities (SNEC) study. Atmospheric Environment, 138: 144–151

Zeng Y, Cao Y, Qiao X, Seyler B C, Tang Y (2019b). Air pollution reduction in China: Recent success but great challenge for the future. Science of the Total Environment, 663: 329–337

Zeng Y, Gu D, Purser J, Hoenig H, Christakis N (2010). Associations of environmental factors with elderly health and mortality in China. American Journal of Public Health, 100(2): 298–305

Zhang C, Ding R, Xiao C, Xu Y, Cheng H, Zhu F, Lei R, Di D, Zhao Q, Cao J (2017). Association between air pollution and cardiovascular mortality in Hefei, China: A time-series analysis. Environmental Pollution, 229: 790–797

Zhang J, Chen Q, Wang Q, Ding Z, Sun H, Xu Y (2019a). The acute health effects of ozone and $PM_{2.5}$ on daily cardiovascular disease mortality: A multi-center time series study in China. Ecotoxicology and Environmental Safety, 174: 218–223

Zhang J, Mauzerall D L, Zhu T, Liang S, Ezzati M, Remais J V (2010). Environmental health in China: progress towards clean air and safe water. Lancet, 375(9720): 1110–1119

Zhang X, Chen X, Zhang X (2018). The impact of exposure to air pollution on cognitive performance. Proceedings of the National Academy of Sciences of the United States of America, 115(37): 9193–9197

Zhang Y, Ding Z, Xiang Q, Wang W, Huang L, Mao F (2019b). Short-term effects of ambient PM_1 and $PM_{2.5}$ air pollution on hospital admission for respiratory diseases: Case-crossover evidence from Shenzhen, China. International Journal of Hygiene and Environmental Health, 224: 113418

Zhang Y, Ni H, Bai L, Cheng Q, Zhang H, Wang S, Xie M, Zhao D, Su H (2019c). The short-term association between air pollution and childhood asthma hospital admissions in urban areas of Hefei City in China: A time-series study. Environmental Research, 169: 510–516

Zhao J, Zhang B, Yang S, Mei H, Qian Z, Liang S, Zhang Y, Hu K, Tan Y, Xian H, Belue R, Jordan S S, Xu S, Zheng T, Du Y (2018). Maternal exposure to ambient air pollutant and risk of oral clefts in Wuhan, China. Environmental Pollution, 238: 624–630

Zhao Y, Hu J, Tan Z, Liu T, Zeng W, Li X, Huang C, Wang S, Huang Z, Ma W (2019). Ambient carbon monoxide and increased risk of daily hospital outpatient visits for respiratory diseases in Dongguan, China. Science of the Total Environment, 668: 254–260

Zheng L, Ou J, Liu M, Chen Y, Tang Q, Hu Y (2019). Seasonal and spatial variations of PM_{10}-bounded PAHs in a coal mining city, China: Distributions, sources, and health risks. Ecotoxicology and Environmental Safety, 169: 470–478

Zhou Y, Liu Y, Song Y, Xie J, Cui X, Zhang B, Shi T, Yuan J, Chen W (2016). Short-term effects of outdoor air pollution on lung function among female non-smokers in China. Scientific Reports, 6(1): 34947

Zhu F, Ding R, Lei R, Cheng H, Liu J, Shen C, Zhang C, Xu Y, Xiao C, Li X, Zhang J, Cao J (2019). The short-term effects of air pollution on respiratory diseases and lung cancer mortality in Hefei: A time-series analysis. Respiratory Medicine, 146: 57–65

Zhu J, Zhang X, Zhang X, Dong M, Wu J, Dong Y, Chen R, Ding X, Huang C, Zhang Q, Zhou W (2017). The burden of ambient air pollution on years of life lost in Wuxi, China, 2012–2015: A time-series study using a distributed lag non-linear model. Environmental Pollution, 224: 689–697

Zhu S, Xia L, Wu J, Chen S, Chen F, Zeng F, Chen X, Chen C, Xia Y, Zhao X, Zhang J (2018). Ambient air pollutants are associated with newly diagnosed tuberculosis: A time-series study in Chengdu, China. Science of the Total Environment, 631–632: 47–55

Zhu Y, Wang Z, Yang J, Zhu L (2020). Does renewable energy technological innovation control China's air pollution? A spatial analysis. Journal of Cleaner Production, 250: 119515

Zou B, You J, Lin Y, Duan X, Zhao X, Fang X, Campen M J, Li S (2019). Air pollution intervention and life-saving effect in China. Environment International, 125: 529–541