Impact of air pollution on the burden of chronic respiratory diseases in China: time for urgent action

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In China, where air pollution has become a major threat to public health, public awareness of the detrimental effects of air pollution on respiratory health is increasing—particularly in relation to haze days. Air pollutant emission levels in China remain substantially higher than are those in developed countries. Moreover, industry, traffic, and household biomass combustion have become major sources of air pollutant emissions, with substantial spatial and temporal variations. In this Review, we focus on the major constituents of air pollutants and their impacts on chronic respiratory diseases. We highlight targets for interventions and recommendations for pollution reduction through industrial upgrading, vehicle and fuel renovation, improvements in public transportation, lowering of personal exposure, mitigation of the direct effects of air pollution through healthy city development, intervention at population-based level (systematic health education, intensive and individualised intervention, pre-emptive measures, and rehabilitation), and improvement in air quality. The implementation of a national environmental protection policy has become urgent.

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Introduction

Air pollution is a major environmental issue affecting respiratory health globally. The most notorious events to occur were in Los Angeles, CA, USA, in 1943 and London, UK, in 1952, and were mainly attributable to coal combustion and traffic emission, which were characterised by different types and levels of pollutants, particularly sulphur dioxide and nitrogen dioxide. During photochemical events in Los Angeles, atmospheric ozone levels surged to more than 0·6 ppm, and in London black carbon levels reached 1400 μg/m³ and sulphur dioxide levels reached 0·7 ppm.[1] The adverse impacts of air pollution on health have been enormous. Disability-adjusted life-years (DALYs) for air pollution worldwide were 157 831 000 in 1990 and 141 456 000 in 2013.[2] In this period, despite a 20·4% reduction in the effect of household air pollution and a 3·0% reduction on the effect of particulate matter (PM), the influence of ambient ozone on DALYs increased by 32·5%.[2] Serious air pollution events in developed countries have prompted industrial technological upgrading, establishment of stringent standards for industrial and traffic-related pollutant emission, setting up of air management bureaus, and launch of laws to control emissions, such as the UK's Clean Air Act.[1]

China is a major developing country with rising levels of air pollution from industrial and traffic emissions coupled with natural phenomena (dust-haze events).[3] Air pollution in China is mainly different from that in developed countries in terms of its magnitude. This difference is exemplified by severe air pollution events such as that recorded during 2011–14 in the North China Plain,[4] when the highest annual level of fine PM exceeded 690 μg/m³. Ambient air pollutant emissions and the resulting health burden have increased annually since 1990. Despite continued increase in pollutant emissions within the past decade, atmospheric air pollutant levels have been progressively declining, albeit at a small rate, and this decline is projected to either plateau or fall further in the long run if the active implementation of management measures by the Chinese Government is successful (figure 1).[5–7] In China, household air pollution is the top risk factor for premature deaths.[8] With urbanisation increasing from 26% in 1990 to 50% in 2010,[9] China has undergone dramatic epidemiological transitions.[10] From 1990 to 2013, deaths across all ages have remained steady (1·8% increase) whereas age-standardised mortality has decreased by 46·2% for chronic respiratory diseases.[11] Despite DALYs attributed to outdoor PM exposure having increased from 1990 to 2010 (13 452 000 *vs* 16 068 000),

Search strategy and selection criteria

We searched PubMed from Jan 1, 2000, to May 15, 2016, for the terms "chronic respiratory disease", "asthma", "wheeze", "chronic obstructive pulmonary disease", "COPD", and "lung cancer", plus either of the following specific terms: "air pollution", "air pollutant", "particulate matter", "haze", "carbon monoxide", "sulfur dioxide", "sulfur oxides", "nitrogen dioxide", "nitrogen oxides", "NO_2", "NOx", "ozone", "O_3", "$PM_{2·5}$", "PM_{10}", "polycyclic aromatic hydrocarbon", "aldehyde", and "China". Our search was based solely on references published in English. In view of the limited literature reports from China, we assigned priority to meta-analyses or reviews from China, followed by highly relevant and influential original articles published in major medical journals that documented the association between air pollution and chronic respiratory diseases. In case of no available references from China, we included highly relevant literature from abroad (eg, the Global Burden of Disease Study, WHO reports, Royal College of Physicians of London reports, *The Lancet* Commissions, and articles related to London air pollution events, the delayed effects of air pollution on respiratory health, respiratory risks of air pollution in middle-to-low-income countries, the relationship between pollutant exposure and COPD or cancer risks, the economics and air pollution in Australia, the particulate monitor use, and effects of interventions to ameliorate respiratory symptoms).

DALYs attributed to household air pollution have decreased (21 923 000 *vs* 12 382 000), indicating that household air pollution causes more substantial adverse effects than does ambient air pollution in China.[10] Air pollution is an immense burden for China's health care, with cardiovascular and circulatory diseases being the most prevalent, followed by chronic respiratory diseases (table 1).

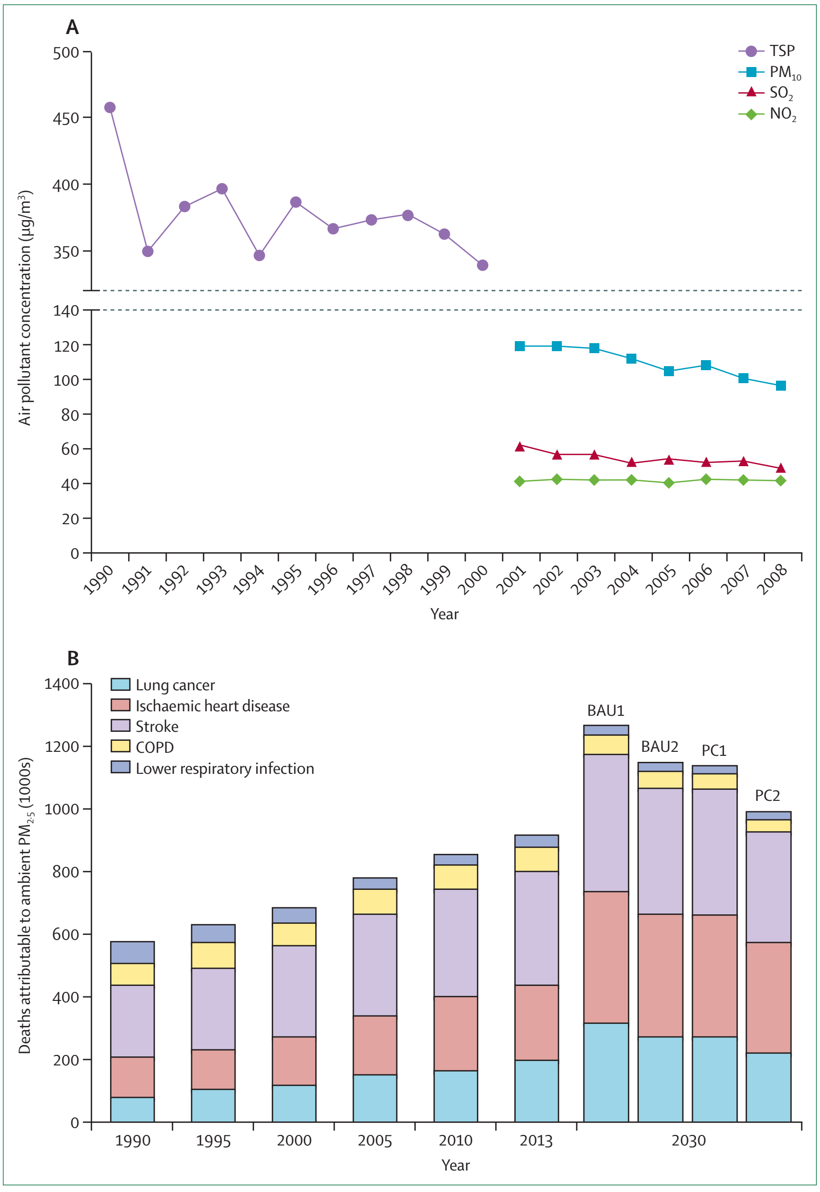

Figure 1: **Air pollution concentrations and effect on mortality in China**

(A) TSP used to be the major source of atmospheric air pollution monitoring. PM_{10} was introduced in air pollution monitoring in 2001 but $PM_{2.5}$ was routinely monitored throughout China only in 2012. Data on air pollution throughout China from 2009 onwards are not available, despite reports of air pollution trends in certain cities. Data from Zhou and colleagues[5] and Kan and colleagues.[6] (B) Because of the well-recognised pronounced adverse impacts on population health, $PM_{2.5}$ was used to represent major air pollutant. Predictions for 2030 are made according to different scenarios: BAU1=current legislation and implementation status as of end of 2012 for 12th Five-Year Plan for Environmental Protection; BAU2=current legislation and implementation status as of end of maximum feasible emission controls regardless of cost; PC1=additional energy saving policies will be implemented, including lifestyle changes, structural adjustments, and energy efficiency improvements, for 12th Five-Year Plan for Environmental Protection; PC2=additional energy saving policies will be implemented, including lifestyle changes, structural adjustments, and energy efficiency improvements, for maximum feasible emission controls regardless of cost. Data from Health Effects Institute.[7] TSP=total suspension particle. PM_{10}=particulate matter of diameter ≤10 μm. $PM_{2.5}$=particulate matter of diameter ≤2·5 μm. SO_2=sulphur dioxide. NO_2=nitrogen dioxide. COPD=chronic obstructive pulmonary disease.

China still relies heavily on coal consumption, which accounts for 64% of domestic energy consumption (worldwide average level 30%). Meanwhile, its rapid economic development has contributed to increased energy use and industrial waste associated with rising levels of air pollution (eg, total yearly carbon dioxide emission increased from ~2000 billion kg in 1980 to ~5000 billion kg in 2000),[12] thus threatening public health.[13]

Chronic respiratory diseases represent a substantial health-care burden in China. Chronic obstructive pulmonary disease (COPD) and lung cancer are respectively the third and fourth most common causes of mortality, with 910 809 deaths attributed to COPD, 546 259 to lung cancer, 82 328 to interstitial lung disease and sarcoidosis, and 25 163 to asthma in 2013.[10] Lung cancer was a leading cause of DALYs in China, and ambient and household air pollution ranked fourth and fifth, respectively, as risk factors that contributed most to DALYs.[10] Findings suggest that smoke from incomplete combustion of biomass fuel predisposes to COPD pathogenesis.[14] Each 10 μg/m³ rise in fine PM, of any origin, has been linked to a 3·1% increase in risk of hospitalisation and a 2·5% increase in mortality.[15] Implementation of effective measures to minimise pollutant emissions is needed and will lead to an improvement in respiratory health in China.

Here, we focus on air pollutants and their effects on chronic respiratory diseases, highlighting targets for interventions (particularly for at-risk populations), and recommendations to improve air quality.

Components and sources of air pollutants

Outdoor air pollutants and haze

PM is mainly derived from natural phenomena (eg, desert wind storms), anthropogenic and industrial activities, and traffic-related sources through the combustion of coal and petroleum products. PM_{10} refers to particles of diameter 10 μm or less, $PM_{2.5}$ to those of diameter 2·5 μm or less, and ultrafine particles to those less than 0·1 μm in diameter. Inorganic gaseous pollutants (eg, carbon monoxide, sulphur dioxide, and nitrogen dioxide), which primarily originate from biomass fuels, coal, and petroleum combustion products, have been implicated in haze formation.[16] These components interact with ozone following sunlight exposure, forming an irritating photochemical cocktail termed smog. Volatile organic compounds react with atmospheric oxidants, generating secondary organic aerosols that interact with atmospheric sulphate, nitrate, and ammonium, leading to PM and haze formation.

Haze days (daily visibility <10 km with relative humidity <90%) are extreme events that frequently elicit exacerbation of chronic respiratory diseases, particularly during cold winters and in males (because of increased exposure to outdoor air pollution) and the elderly.[17] Haze events have become so frequent that they are known as Chinese haze.[18]

Indoor air pollutants

Indoor air pollutants include household air pollutants, second-hand tobacco smoke, furniture-derived formaldehyde, nitrogen oxides from natural gas appliances, and volatile organic compounds from new house construction. Second-hand tobacco smoke is a serious issue because of the 350 million cigarette smokers in China, where smoking rates have remained steady[19] despite various measures banning tobacco advertising, sponsorship, and promotion.

We focus on household air pollutants, which primarily originate from cooking with poor ventilation or heating stoves using biomass, coal, and other solid fuels. Apart from common pollutants, microfibrous quartz and other toxic elements (eg, fluoride, arsenic) are derived from coal combustion. Frequent occupational exposures to irritant vapours, gases, dusts, and fumes, coupled with high levels of second-hand tobacco smoke, might contribute to development of COPD in non-smokers. In China, decreased household air pollution during rapid urbanisation has been closely associated with a reduced burden of chronic respiratory diseases. Consequently, decreased risk of chronic respiratory diseases would be expected in individuals who come from rural areas with severe household air pollution and subsequently reside in urban areas with poor outdoor air quality but improved household air quality. In fact, incomplete combustion of biomass fuel is responsible for the high prevalence of COPD in Chinese never-smokers, with a 12% prevalence in Yunyan (Guangdong).[13] Exposure to indoor air pollution caused by combustion of smoky coal, which is rich in volatile compounds producing more abundant air pollutants, has been associated with increased risks of lung cancer in Xuanwei, Yunnan.[20] Children and women are more frequently exposed to high levels of household air pollution, which warrants targeted interventions in these at-risk groups.[21]

Air quality standards

In light of severe air pollution and increasing respiratory disease morbidity, China has implemented measures to reduce the impact of air pollution on public health. Despite the standards being less stringent, China has adopted the updated air quality standards (table 2). The Chinese air quality index (AQI), which resembles that of the USA, has incorporated protection measures for individual thresholds of air pollution (figure 2).

Variation and time-scale trends of air pollution

Air pollution varies considerably among different regions.[27] Analysis of data from 2001 to 2012 showed higher annual cumulative air pollution index (API)—an integrated parameter of levels of nitrogen oxides, sulphur dioxide, and PM_{10} to inform citizens of daily atmospheric air pollution—in northwest (~1400 in Lanzhou) and northeast China (~1050 in Shenyang) than in southeast (~750 in Fuzhou) and southwest China (~850 in Guiyang).[28] A study[29] conducted between 2013 and 2014 showed higher levels of $PM_{2·5}$, PM_{10}, carbon monoxide, and sulphur dioxide in capital cities in north China than in those in western and southeastern China. Industrial PM emissions in China are mainly from the Bohai economic area where iron and steel smelting plants were densely built.[30] Solid waste incineration is another source of hazardous air pollutant emission, most of which is concentrated in eastern-central and southeast China where incineration plants were built; Zhejiang, Guangdong, and Jiangsu topped the list of hazardous air pollutant emission between 2003 and 2010.[31] Within-urban variations in air pollutants have also been documented. In Beijing, significantly higher annual PM_{10} levels were observed in Shijingshan (IQR 96·0 μg/m³) than in Chaoyang (83·5 μg/m³), relating to differences in distribution of industry, road types, and urban infrastructure.[32]

	Chronic respiratory diseases	Cardiovascular and circulatory diseases	Cancer
Ambient air pollution			
Mean DALYs	3 113 077	18 126 714	3 063 087
DALYs (%)	0·98	5·71	0·97
Mean mortality	196 202	887 850	139 369
Mortality (%)	2·36	10·69	1·68
Household air pollution			
Mean DALYs	4 893 529	13 697 007	1 580 598
DALYs (%)	1·54	4·32	0·50
Mean mortality	309 206	646 373	72 303
Mortality (%)	3·72	7·78	0·87

Total mortality in China was 8 303 700 and total disability-adjusted life-years (DALYs) were 317 209 000. Data from Yang and colleagues.[10]

Table 1: **Burden of disease associated with air pollution in China in 2010**

Although the API in China has slightly decreased since 2001,[28,33] pollutant emission from iron and steel industries[30] and other sources is progressively increasing.[11,31] Seasonal variations in air pollution show that significantly more non-attainment days have been recorded in winter than in other seasons, whereas high-pollution days have been frequently recorded in southeast China in autumn and in west China in spring.[29] Despite continued improvements in air quality in China from 2001 to 2011, substantial temporal variation in air pollution was observed. Reduction in API was maximal during 2001–04, and the API reached its lowest levels in 2011.[28] In three different cities of north China (Beijing, Shijiazhuang, and Tianjin), concentrations of polycyclic aromatic hydrocarbons (PAHs) in PM were increased in winter and spring seasons when

	US EPA concentration[22]	China concentration[23]	Europe concentration[24]	WHO concentrations[25]
Sulphur dioxide (SO_2)				
1 h	75 ppb	500 μg/m³	350 μg/m³	..
3 h	0·5 ppm	..	..	..
24 h	..	150 μg/m³	125 μg/m³	IT-1: 125 μg/m³; IT-2: 50 μg/m³; AQG: 20 μg/m³
1 year	..	60 μg/m³	..	..
Carbon monoxide (CO)				
1 h	35 ppm	10 mg/m³	..	..
8 h	9 ppm	..	10 mg/m³	..
24 h	..	4 mg/m³	..	..
Lead (Pb)				
3 months	0·15 μg/m³	..	..	..
1 year	..	..	0·5 μg/m³	..
Nitrogen dioxide (NO_2)				
1 h	100 ppb	200 μg/m³	200 μg/m³	200 μg/m³
24 h	..	80 μg/m³	..	..
1 year	53 ppb	40 μg/m³	40 μg/m³	40 μg/m³
Ozone (O_3)				
1 h	..	200 μg/m³	..	..
8 h	0·07 ppm	160 μg/m³	120 μg/m³	IT-1: 160 μg/m³; AQG: 100 μg/m³
$PM_{2·5}$				
24 h	35 μg/m³	75 μg/m³	..	IT-1: 75 μg/m³; IT-2: 50 μg/m³; IT-3: 37·5 μg/m³; AQG: 25 μg/m³
1 year	12 μg/m³	35 μg/m³	25 μg/m³	IT-1: 35 μg/m³; IT-2: 25 μg/m³; IT-3: 15 μg/m³; AQG: 10 μg/m³
PM_{10}				
24 h	150 μg/m³	150 μg/m³	50 μg/m³	IT-1: 150 μg/m³; IT-2: 100 μg/m³; IT-3: 75 μg/m³; AQG: 50 μg/m³
1 year	..	70 μg/m³	40 μg/m³	IT-1: 70 μg/m³; IT-2: 50 μg/m³; IT-3: 30 μg/m³; AQG: 20 μg/m³

WHO interim targets (ITs) describe several stages for pollutant emission control, corresponding with progressive reductions in mortality risk. IT-1 is the first upper limit of pollutant emission control, followed by successive lowerings of the upper limit. The final goal is typically expressed as the air quality guideline (AQG), which marks the lowest level at which total, cardiopulmonary, and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to $PM_{2·5}$. US EPA=United States Environmental Protection Agency. $PM_{2·5}$=particulate matter of diameter ≤2·5 μm. PM_{10}=particulate matter of diameter ≤10 μm.

Table 2: **Ambient air quality standard over different averaging periods in the USA, China, Europe, and WHO's criteria**

See Online for appendix

For the **National Ambient Air Quality Standards** see https://www.epa.gov/criteria-air-pollutants

central heating use was at its peak.[34] Assessment of daily levels showed time-dependent variation in air quality, with lower values in the afternoon (1300–1800 h) and higher values in the evening (1900–0000 h).[28]

Moreover, the API was negatively correlated with temperature, relative humidity, wind speed, and precipitation, and positively correlated with atmospheric pressure and diurnal temperature range.[33] These findings highlight the importance of consideration of the spatial and temporal variations of air pollutants.

Impact of air pollution on chronic respiratory diseases

Owing to the limited literature from China and the substantial differences in study design, pollutant types, and outcome measures in the small number of studies, a meta-analysis has not been performed for all respiratory diseases, but important findings from the individual studies have been summarised (figure 3, appendix).

Adverse effects of air pollutants on the lungs include disruption of airway epithelial barrier and cellular signalling pathways,[35–37] parenchymal destruction,[36,37] oxidative stress,[35,37–41] impairment of phagocytosis,[39] inflammatory cell infiltration,[38,39] dysregulated cell immunity,[38–41] epigenetic modifications,[42] and autophagy[43] (figure 4). The US Environmental Protection Agency has set the National Ambient Air Quality Standards for six common air pollutants, and has described the mechanisms by which air pollutants trigger airway injury.

Asthma

Air pollution contributes to increased asthma prevalence and symptom onset.[44] Many developing countries or regions (eg, rural China, India, and Malawi) still use open fires for cooking. Despite mixed findings for biomass smoke exposure and asthma risk, coal combustion for heating (odds ratio [OR] 1·5; 95% CI 1·1–1·9) and cooking (2·3; 1·5–3·5) conferred higher risks of childhood asthma in China.[45] Each 10 μg/m³ increase in nitrogen dioxide corresponded to an adjusted OR of 1·25 (95% CI 1·16–1·36) for diagnosed asthma in 6–13-year-old Chinese children.[46] Environmental tobacco smoke and chemical emissions from new furniture were risk factors for asthma[47] and for wheeze and daytime breathlessness amongst pupils.[48] Males without allergic predisposition and females with allergic predisposition had increased susceptibility to the adverse impact of air pollution on asthma.[49] The explanation for this is unclear, but could be related to the different airway responses of males and females to air pollutants, and the greater airway sizes in boys than in girls.[49]

Increased ambient ozone, nitrogen dioxide, $PM_{2·5}$, and sulphur dioxide levels were associated with increased hospital admission for asthma.[50–54] In multi-pollutant models, black carbon (risk ratio [RR] 1·06; 95% CI 1·05–1·07) conferred greater asthma admission risks than did $PM_{2·5}$ (1·03; 1·02–1·05), with a maximum of a 3-day lag for children in Shanghai, following stratification by age, sex, and season.[55]

Moreover, the adverse effects of air pollution could be long lasting. In China, each 15 μg/m³ and 50 μg/m³ increase in nitrogen dioxide and sulphur dioxide levels was associated with an adjusted OR of 1·90

	Level of health concern (USA)	Level of health concern (China)	Health effect	Protection measures (China)
Green	Good	Good	Air quality is considered satisfactory, and air pollution poses little or no risk	Normal activity can be performed
Yellow	Moderate	Fair	Air quality is acceptable; however, for some pollutants there might be a moderate health concern for a very small number of people who are unusually sensitive to air pollution	A very small number of affected people should avoid outdoor activity
Orange	Unhealthy for sensitive groups	Mild pollution	Members of sensitive groups might experience health effects; the general public is not likely to be affected	Children, the elderly, and patients with cardiovascular or respiratory diseases should avoid intense outdoor activity over a long period
Red	Unhealthy	Moderate pollution	Everyone might begin to experience health effects; members of sensitive groups might experience more serious health effects	Children, the elderly, and patients with cardiovascular or respiratory diseases should avoid intense outdoor activity over a long period; the general public should reduce some outdoor activity
Purple	Very unhealthy	Severe pollution	Health warnings of emergency conditions; the entire population is more likely to be affected	Children, the elderly, and patients with cardiovascular or respiratory diseases should stay at home and stop outdoor activities; the general public should reduce outdoor activity
Maroon	Hazardous	Serious pollution	Health alert: everyone might experience more serious health effects	Children, the elderly, and patients with cardiovascular or respiratory diseases should stay at home and avoid physical exertion; the general public should avoid outdoor activity

***Figure 2:* Specification of air quality index and protection measures**
The formula for calculating the air quality index in China and the USA is similar except different thresholds of air pollutants are used. Moreover, the Chinese version has adopted different levels of health concern, and has offered details regarding measures that should be taken when pollutant levels are above certain thresholds. Data from the US Environmental Protection Agency.[26]

(95% CI 1·20–3·00) and 1·62 (1·01–2·60) for asthma, respectively, whereas combined exposure to high levels of nitrogen dioxide and sulphur dioxide further increased the OR to 1·85 (1·22–2·79) in the first year of life.[56] A report[57] in the USA has shown that early-life exposure to traffic-related air pollution correlated with the OR for forced vital capacity and forced expiratory volume in 1 s (FEV_1) being less than the lower-limit-of-normal of 4·3 (1·2–15·0) and of 3·8 (1·3–10·9), respectively.

With the population of China (~1·4 billion in 2015) and the high prevalence of asthma (~1·24% of residents older than 14 years),[58] the adverse effect of air pollution on respiratory health represents a substantial burden with regard to disease prevention and management.

COPD

Outdoor air pollution has contributed to increased incidence and prevalence of COPD.[59] In China, the prevalence of COPD was 5·2% among non-smokers, in whom household pollutants (eg, coal and wood smoke) might have contributed to development of COPD.[60,61] Following use of improved household stoves in Xuanwei (Yunnan), the RR for COPD incidence was 0·58 (95% CI 0·49–0·70) in males and 0·75 (0·62–0·92) in females, which was lower than that in lifelong non-users.[59] Poor ventilation and cooking with biomass fuel in Yunyan (Guangdong) led to higher indoor sulphur dioxide (0·25–0·50 mg/m³ *vs* 0·15 mg/m³) and PM_{10} (0·10–1·00 mg/m³ *vs* 0·15 mg/m³) levels than in urban households in Liwan, Guangzhou, where clean fuels and electricity were used.[14,62] After a 9-year follow-up, use of clean fuels (biogas instead of biomass) plus improved ventilation was associated with slower decline in FEV_1 (mean 16 mL/year) and lower OR (0·28) of development of COPD when compared with either use of clean fuels or improved ventilation, or neither.[62]

Air pollution, including dust storms, predisposes to COPD exacerbation needing hospitalisation in Xuanwei, Jinan, and in Hong Kong.[60,63,64] In four-pollutant models of Hong Kong, the RR for COPD admission per 10 μg/m³ increase in ozone was 1·029 (95% CI 1·022–1·036) and 1·014 (1·007–1·022) per 10 μg/m³ increase in $PM_{2·5}$.[65] Air pollution has contributed to mortality associated with COPD in Shanghai,[66] despite a report[67] documenting that each 0·4 ppm increase in carbon monoxide levels has been negatively correlated with COPD admissions (mean –1·8%; 95% CI –3·1 to –0·4), with stronger effects following adjustment for nitrogen dioxide and $PM_{2·5}$ levels. Air pollution has caused long-lasting adverse effects on COPD mortality, which warrants closer follow-up in at-risk populations.[68]

Data from a global analysis[69] show that dose–response relationships between air pollution and COPD mortality are non-linear, with mortality risks increasing rapidly at low $PM_{2·5}$ levels (<100 μg/m³) and reaching a plateau at higher levels (>300 μg/m³). This plateau level can be applied to the Chinese population with regard to air pollutant levels throughout China.

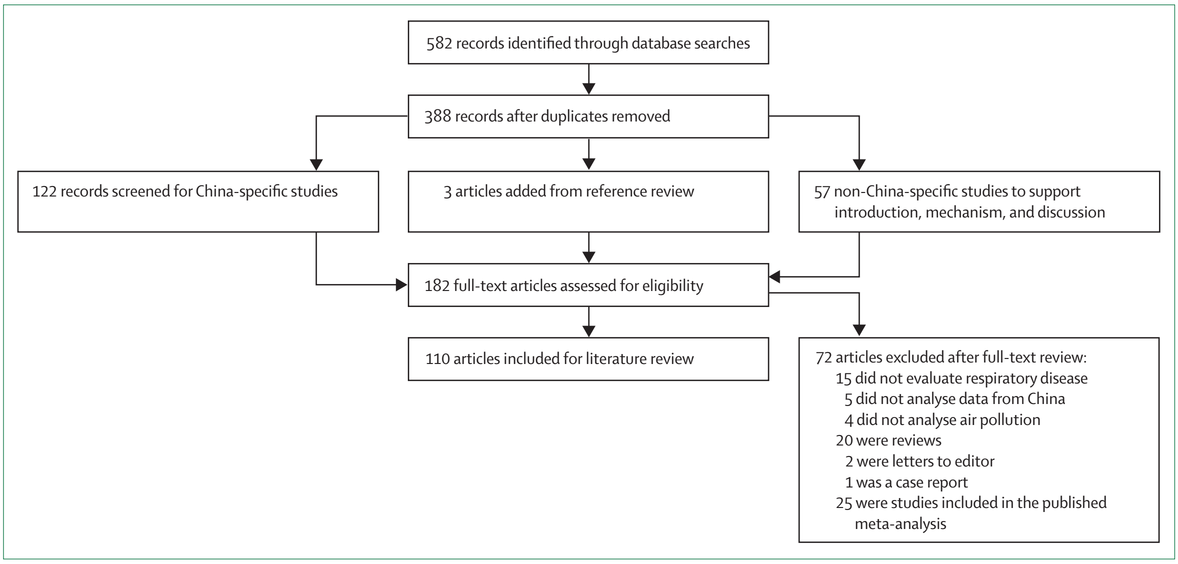

***Figure 3*: Flow chart of the literature review**

Lung cancer

Smoking and solid-fuel (eg, coal and wood) combustion predispose to lung cancer,[70] with spatial and gender variation. Time-based multiple risk factor models have shown smoking and solid-fuel use collectively contributed to 75% of lung cancer deaths in China.[71] Each 10 μg/m³ increase in 2-year average $PM_{2·5}$ correlated with an increased risk of lung cancer in males (RR 1·055; 95% CI 1·038–1·072) and females (1·149; 1·120–1·178).[72] Household coal use has been associated with increased lung cancer risks in mainland China and Taiwan (OR 2·27, 95% CI 1·65–3·12), particularly in southern and southeastern (3·27; 1·27–8·42) and southwestern China (2·98; 1·18–7·53).[73] In individuals who used domestic coal for cooking and heating, pooled ORs were 2·66 (95% CI 1·39–5·07) for both genders and 1·83 (0·62–5·41) for females. Other studies also suggest that both indoor and outdoor air pollution play crucial roles in lung cancer pathogenesis in the Chinese population.[74–82] Pooled risks for exposure to cooking oil vapour (OR 2·12; 95% CI 1·81–2·47) were higher than were those for cigarette smoking in non-smoking females (1·70; 1·32–2·18).[83] Indeed, improved indoor ventilation, which increases air quality, has been associated with a lower incidence of lung cancer.[84]

Smoky coal used to be a major source of fuel in rural China. In Xuanwei, where lung cancer mortality is very high,[20,85] smoky coal conferred greater risks than did non-smoky coal or other fuels, possibly owing to high PAH levels from smoky coal.[86,87]

Targets for intervention

Air pollution contributes substantially to respiratory disease burden.[88] Exposure to PM_{10} at 20 μg/m³ in Lanzhou resulted in economic costs associated with respiratory diseases of 0·194% of the gross domestic product in China (0·175% for exposure at 50 μg/m³).[89] In Australia, where air pollution levels are much lower than in China, $PM_{2·5}$ levels contributed to 430 premature deaths (95% CI 310–540, accounting for ~2% of total deaths), 5800 years of life lost (3900–7600, accounting for 1·8% of total years of life lost) and 630 respiratory or cardiovascular hospital admissions (410–480) in 2007 alone.[90] A 10% reduction in $PM_{2·5}$ levels in 2007 would have led to 650 premature deaths (430–850), 3500 years of life gained (2300–4600), and 700 fewer respiratory or cardiovascular hospital admissions (450–930) over the following decade.[90] Therefore, effective measures to reduce exposure to air pollution—both at an organisational (figure 5) and personal level—can lead to substantial economic benefit.

Addressing environmental health in all sectors

Various organisation-level approaches have been proposed by the Royal College of Physicians of London[91] and *The Lancet*.[92–94] WHO suggest that engagement of health-care professionals can effectively integrate health into environmental protection policies.[88] From lessons learnt abroad, the Chinese central Government has prioritised environmental protection in the 13th Five-Year Plan to cut carbon dioxide emission by 18% by 2020, and has implemented serial measures to mitigate air pollution.[95] For city and local government, downtown industrial facilities will be fined for excessive discharge via a dynamic surveillance system. Establishment of national accountability would secure implementation of air quality control more effectively than just through air quality monitoring.[92] Air quality in Pearl River Delta has been improved through establishment of collaborative prevention and control systems, prioritisation of air

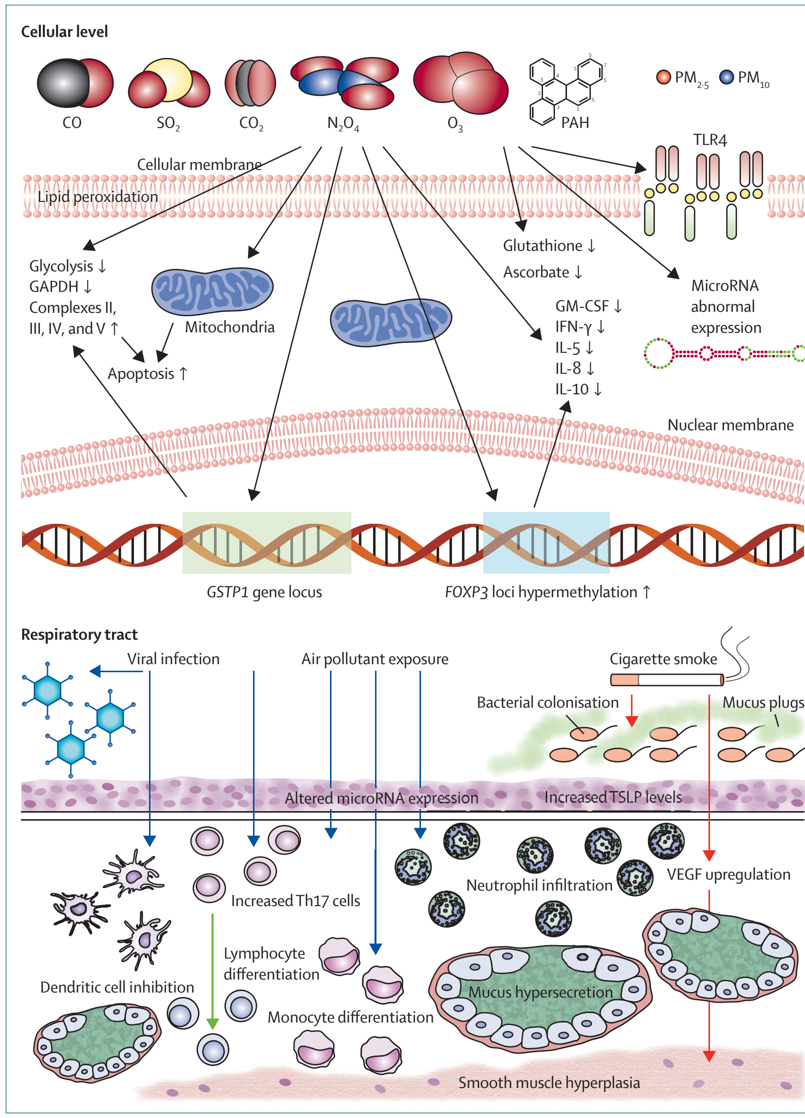

***Figure 4:* Pathways acted on by air pollutants in the respiratory tract and cells**
PAH=polycyclic aromatic hydrocarbon. IFN=interferon. IL=interleukin. GM-CSF=granulocyte macrophage-colony stimulating factor. TSLP=thymic stromal lymphopoietin. VEGF=vascular endothelial growth factor.

pollution management, and incorporation of control of $PM_{2·5}$ levels in political achievement assessment.

The transportation sector plays a crucial role in reduction of traffic-related air pollution, which has substantial adverse effects on respiratory health. Individuals exposed to traffic-related air pollution had a 4·19 times (95% CI 2·49–7·06) higher risk of chronic pharyngitis, a 3·90 times (2·61–5·81) higher risk of sputum production, a 1·96 times (1·11–3·46) higher risk of chronic rhinitis, and a 1·95 times (1·55–2·46) higher risk of throat pain.[4,96] Commuters are exposed to PM and PM-bound PAHs on a daily basis.[97] The substantial reduction in air pollution following effective traffic control during the 2008 Beijing Olympic Games[98] and the 2010 Guangzhou Asian Games[99] has lent support to the concept that reductions in traffic-related air pollution emission lead to an improvement in public health. In China, development of green and low-carbon engines or vehicles with increased availability of public transport systems, as requested by the transportation and energy sectors, appears successful, but is challenging because of high cost issues.[100] The Chinese Government has established policies to subsidise electric and hybrid car purchases in Shanghai, Shenzhen, Hangzhou, Changchun, and Hefei,[101] and has built infrastructural facilities to provide electrical charging for hybrid vehicles. Although stricter regulations have limited car ownership and entry into major roads during rush hours in megacities, promotion of public transportation, establishment of intelligent transportation management systems, and integrated city development goals are needed. The energy sector should play a greater role by building environmentally friendly wind, water, and solar power plants. Pollutant emission would be decreased through reduction in coal transportation by rail from north to south.

Environmental health cannot be achieved by government agencies alone. Research institutions should be actively engaged in the development of efficient technologies to reduce air pollution. Strict observance of laws and regulations is a principal duty for individual corporations. Finally, education in schools regarding precautions to take to limit the detrimental effects of air pollution should be instituted.

Fuel and vehicle upgrading

Most vehicles in China use petrol, followed by diesel. Pollutant emission per vehicle in China remains higher than that in developed countries despite similar emission standards. In Guangzhou, $PM_{2·5}$/km per vehicle is 1·2–5·0 times higher than in developed countries, with carbonaceous aerosols 1·3–4·2 times higher, and aromatic hydrocarbon emission 2·0–3·0 times higher.[102] Stricter emission standards should be established for petrol-based and diesel-based engines or vehicles.

Lead-based anti-knock addictive has been banned, with the use of low or ultra-low sulphur diesel. In 2013, the fifth National Vehicle Gasoline Standard provided the minimum upper limits of sulphur (<10 ppm), manganese (<2 mg/L), and alkenes (<25%). The Chinese Government has phased out yellow-label vehicles (petrol and diesel vehicles that fall below national 2 and 3 emission standard, respectively) in prefecture-level cities. This move will decrease sulphur dioxide emission by 80% and nitrogen dioxide emission by 0·3 million tons annually.

Since 2008, hybrid public vehicles harnessing liquid natural gas and electricity have gained in popularity, which could lead to a reduction in pollutant emission of 15–35%.

Industrial technology upgrading

Progressively increasing coal production and consumption in China, which was higher than the rest of the world combined in 2012 (~4·0 billion tons), is the main

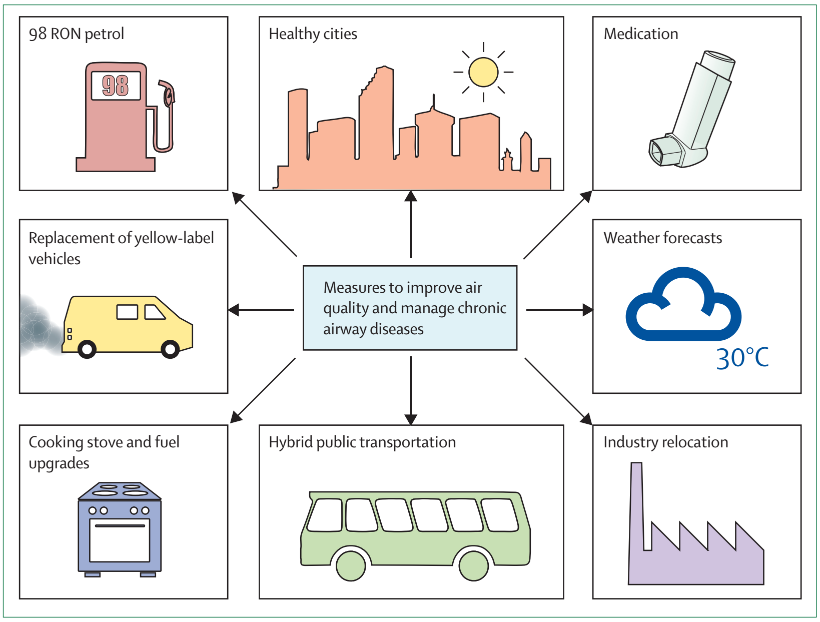

Figure 5: **Measures to improve air quality and manage chronic airway diseases**
Measures mainly include novel medications, incorporation of $PM_{2\cdot5}$ levels in weather forecasts, industrial upgrading, renovation of vehicle fuel and public transportation, improving cooking fuel and ventilation, building up healthy cities, and implementing environmental policies. RON=research octane number. $PM_{2\cdot5}$=particulate matter of diameter ≤2·5 μm.

cause of air pollution.[103] Technological upgrading of coal production and combustion facilities is warranted. Factories should be upgraded and relocated to suburban areas. Removal of a cement factory (a major source of industrial air pollutant emissions) from downtown Guangzhou—a pivotal action taken to improve community air quality in Liwan—was associated with reduced sulphur dioxide concentration (a decline of 0·051 μg/m³ annually) and dust deposition (a decline of 0·051 kg/km² per month), and a slower FEV_1 decline (mean difference 19 mL/year).[104]

For **China's $PM_{2\cdot5}$ levels** see http://www.pm25.org.cn/

Legislation to ban smoking

Although the Chinese Government has banned tobacco advertising, sponsorship, and promotion of tobacco products, the smoking rate remains steadily high.[105] China should legislate to restrict tobacco production (particularly in Yunnan, Guizhou, and Sichuan), regulate e-cigarettes, use illustration of deleterious effects on cigarette packages as aversion therapy, and propagate a healthy, smoking-free culture.

Healthy cities

Healthy cities have become the prime goal for sustainable development. Beyond clean water sources, energy supply, improved access to health-care facilities, continuous improvements in health-care quality, rapid transport systems, healthy living, and stringent policies that protect citizens' rights and welfare, clean air remains an essential element. However, the 2015 *Blue Book of Cities in China* indicated that 90% of cities were subhealthy, whereas only 23 cities were healthy (eg, Zhongshan and Foshan). The Government and environmental experts should jointly develop more efficient policies (eg, rigorous pollutant emission standards, subsidisation of electric and hybrid car purchases to phase out yellow-label cars, promotion of development of public transport systems, and reinforcement of forestation in urban areas) to improve air quality.

Reduced levels and transition to low-carbon energy

Reforestation of grain plots or deserts would eliminate 183 gigatons of carbon emission by 2060, and direct air capture techniques (eg, point-source capture with a highly efficient sorbent) would eliminate 3·6 gigatons of carbon dioxide annually with 10 million air capture units.[92] Carbon intensity reduction is viable: use of solar energy would lead to a reduction of 0·4–15·0 gigatons of carbon dioxide emission annually by 2050, alongside a reduction of 1·2–9·8 gigatons through wind energy.

Solar energy would be the ideal source of energy because it elicits neither carbon dioxide emission nor needs any dramatic landform changes that could predispose to ecological imbalance. Solar energy can be directly harnessed to generate electricity to be used to heat water and for cooking. Unlike wind or water resources, solar energy can be readily applied in different settings (households, workplace, and remote regions). The Chinese Government has increased investment in solar photovoltaic systems, leading to a steady increase in the use of solar energy.[106]

Establishment of early warning systems

Patients at risk are encouraged to stay indoors during haze days. Early warning systems via weather forecasts might be effective in exposure reduction. Real-time display of nationwide $PM_{2\cdot5}$ concentrations is available. Real-time observations of air pollution, particularly for PM, have been made possible by satellite monitoring, and dynamic monitoring over prolonged periods (>4 years) will better clarify time trends of exacerbations. Compared with ground-based air quality monitoring, satellite monitoring has the advantage of providing estimates of exposure to air pollution in areas (eg, rural regions) where stationary monitoring data are not available. Substantial advances in information technology (eg, crowdsourcing and medical mega-databases) should be used to improve intelligent warning systems.[107]

The AQI, which incorporates information on $PM_{2\cdot5}$ levels, is an established parameter for reflecting air quality and has been adopted in China.[108] Although time lag issues might have challenged the validity of the AQI, the Shanghai Air Quality Health Index (SAQHI) might be more readily used by public broadcast and print media to inform citizens when at-risk patients should restrict outdoor activities (table 3).[109] Compared with the AQI, SAQHI better reflects the correlation between air pollution and respiratory health, provides global assessment of daily air pollution, and estimates acute impact on respiratory health. However, studies comparing their usefulness to predict respiratory health risks throughout China are warranted, and extrapolation of SAQHI should be made cautiously.

Feasibility of face masks

At a personal level, wearing face masks is the simplest approach to minimise pollutant exposure. In an open-label trial,[110] patients with coronary artery disease walked on a predefined route in Beijing (mean $PM_{2·5}$ 74 μg/m³), either using highly efficient face masks or no face masks at all. Face masks decreased self-reported symptoms, reduced maximal ST segment depression in an electrocardiogram over 24 h, and lowered arterial blood pressure. A few commercial face masks (eg, N95 masks) can effectively filter outdoor PM and reduce respiratory health risks associated with severe air pollution in individuals, although prolonged wearing (>2 h) can readily lead to breathlessness in healthy individuals. To avoid subjective bias (findings validated in those who tolerated wearing face masks), the usefulness of wearing face masks should be verified over longer periods. Gaseous pollutants cannot be filtered, therefore wearing face masks cannot be the overall solution.

Air filters and monitors

Air filters are effective for reduction of indoor air pollution. In a randomised, double-blind, crossover trial,[111] use of effective air filters in dormitories for 48 h resulted in a 57% reduction in $PM_{2·5}$ levels (from 96·2 to 41·3 μg/m³), which was associated with a 68·1% reduction in serum interleukin-1β, 64·9% reduction in serum soluble CD40 ligand, 32·8% reduction in serum myeloperoxidase, and 17·5% reduction in serum monocyte chemoattractant protein-1 in healthy college students. Systolic and diastolic blood pressure were also reduced, reaffirming the benefits of effective air filters on the cardiopulmonary system. Air filters (transparency ~90%) which remove 95% of $PM_{2·5}$ under high levels of pollution ($PM_{2·5}$ 250 μg/m³) have been developed.[112] Nanofibrous metal-organic framework filters, with high efficiency (88·33% [SD 1·52] for filtering of $PM_{2·5}$ and 89·67% [1·33] for PM_{10}), can continuously and effectively remove air pollutants for 48 h. These filters can selectively capture and retain sulphur dioxide without reducing permeability to fresh air.[113] The effectiveness of air filters in ameliorating daily symptoms has also been shown in patients with asthma.[114,115]

Commercialised portable air monitors might help inform citizens (at-risk populations and patients with chronic respiratory diseases) to restrict outdoor activities during periods of intense air pollution.[116] In light of the substantial effects of household air pollution on respiratory health in China, these monitors could be used to monitor indoor air quality for households near major roads or with poor ventilation. Standardisation of air monitors is also needed to ensure accurate detection of major air pollutants.

	Risk grading	Flag	Susceptible population	General population
0–3	Low	Green	Outdoor activity recommended; restrict outdoor activity for patients with ongoing respiratory or cardiovascular symptoms	Outdoor activity recommended
4–6	Moderate	Blue	Restrict outdoor activity for patients with ongoing respiratory or cardiovascular symptoms	Maintain daily outdoor activity
7–10	High	Orange	Restrict outdoor activity among the elderly, children, and patients with respiratory or cardiovascular diseases	Outdoor activity restricted in case of respiratory or cardiovascular symptoms
>10	Very high	Red	Avoid outdoor activity among the elderly, children, and patients with respiratory or cardiovascular diseases	Avoid outdoor activity

The formula for calculation of SAQHI is SAQHI = 10/17 × [exp(0·000153 × PM_{10}) – 1 + exp(0·000662 × NO_2) – 1] × 10. Both PM_{10} and NO_2 levels are presented as μg/m³. PM_{10}=particulate matter of diameter ≤10 μm. NO_2=nitrogen dioxide.

Table 3: **Recommended health information based on the Shanghai air quality health index (SHAQHI)[109]**

Dietary recommendations

Antioxidant-rich diets (leafy vegetables and fruits) might help to mitigate adverse impacts of air pollution by counteracting oxidative stress. Antioxidant supplementation with vitamin C and E above the minimum dietary requirement led to attenuated nasal inflammation and partially restored antioxidant levels in asthmatic patients exposed to high levels of ozone.[117] N-acetylcysteine supplementation attenuated airway responsiveness by 42% in patients with airway hyper-responsiveness following inhalation of diesel exhaust compared with filtered air.[118] Hence, daily intake of fresh vegetables and fruits or antioxidant medication and vitamins C and E should be promoted as part of healthy living.

Reduced smoke exposure and improved ventilation

Second-hand smoke, derived from indoor cigarette smoking, is prevalent in China and can be associated with persistent cough, phlegm, wheeze, wheeze without asthma, asthma symptoms, and asthma in children.[119] Environmental tobacco smoke exposure could be minimised by policies to prevent smoking in closed public places. Despite availability of smoking cessation clinics and medications (eg, varenicline), smoking rates remain high. Written action plans for smoking cessation might benefit respiratory health of smokers and people exposed to second-hand smoke. In the workplace, a smoke-free environment effectively minimised second-hand smoke exposure,[120] particularly for the at-risk population.

Biomass fuel combustion products account for 88·1% of household air pollution in China.[14] The transition away from cooking with solid fuels should be the primary effort to reduce exposure to biomass combustion. Improved indoor ventilation, through installation of exhaust ventilators or exhaust fans, is also important. Improved cooking stoves and installation of exhausting fans in households in Yunyan have reduced indoor sulphur dioxide (<0·5 mg/m³), carbon monoxide (<50·0 mg/m³), nitrogen dioxide (<0·2 mg/m³), and PM_{10} (<1·0 mg/m³) emission.[107]

Future research direction

Decarbonisation of the power generation sector is crucial to minimise respiratory health risks. China should rapidly develop and deploy low-carbon technologies, reduce coal consumption, reform the electricity market, and implement carbon pricing policies.[91] Crop-residue burning remains common in rural China and many other tropical countries. Knowledge of the respiratory health effects of this activity would offer a valuable rationale for policy makers to implement community-based intervention approaches to reduce personal and population exposure.

Much remains unclear regarding which pollutants account for most of the respiratory effects and specific signalling pathways responsible for eliciting exacerbation of chronic respiratory diseases. How coarse particles from smoky coal interact with major pollutants in eliciting oncogenesis warrants investigation, as do the mechanisms underlying induction of respiratory exacerbation by PAHs and aldehydes originating from traffic, coal burning, and cigarette smoke.[31,121]

China is a vast geographical territory with contrasting climatic characteristics that influence the components and concentrations of air pollutants. Exploration of heterogeneous adverse effects of air pollution would benefit health-care providers in individual regions.[21] Stricter regulations are needed to improve air quality in highly polluted regions such as northeast China. Evaluation of airway responses to air pollution in northern versus southern China, and in Han Chinese versus other ethnic groups, would unravel the mechanisms and predictors of differential adverse effects in different geographic regions and ethnic groups. Most available data have been derived from studies in developed countries where upper limits of pollution have been relatively low (50 μg/m³ for PM_{10}) compared with Chinese levels, and exclusively in white populations. Data examining dose–response relationships at high pollutant levels would be valuable for policy makers to tailor environmental protection regulations in individual regions. Well designed studies should determine whether extreme air pollution is oncogenic or solely irritating to the airways.

Few studies have examined how improved air quality reduces exacerbation of chronic respiratory diseases on a long-term basis. Reassuringly, implementation of air quality-control policies have led to reduced nitrogen dioxide and $PM_{2.5}$ levels, and improved lung function development in boys and girls with and without asthma.[122]

Conclusion

Air pollution contributes to the pathogenesis and exacerbation of chronic respiratory diseases. Drastic measures—including industrial upgrading, quality improvement of vehicles, petrol, cooking fuel, and stoves, environmental health policy implementation, and surveillance—will translate into improved outcomes for patients with chronic respiratory diseases. The ambition and capacity of successful management of air pollution in China might serve as an example for developing countries where respiratory health impacts of air pollution are as serious as in China, if not more so.

Contributors

W-JG and X-YZ drafted the manuscript. KFC and N-SZ critically revised the manuscript and approved the final submission.

Declaration of interests

KFC has received honoraria for participating in Advisory Board meetings regarding treatments for asthma and chronic obstructive pulmonary disease for GlaxoSmithKline, Boehringer Ingelheim, AstraZeneca, Novartis, and Johnson & Johnson, and has received grant funding through his institution from Pfizer, GlaxoSmithKline, and Merck. He has also been renumerated for speaking engagements by AstraZeneca, Merck, and Novartis. The other authors declare no competing interests.

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