Front. Environ. Sci. Eng. 2024, 18(6): 68
https://doi.org/10.1007/s11783-024-1828-z

PERSPECTIVES

Challenges and perspectives of air pollution control in China

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HIGHLIGHTS

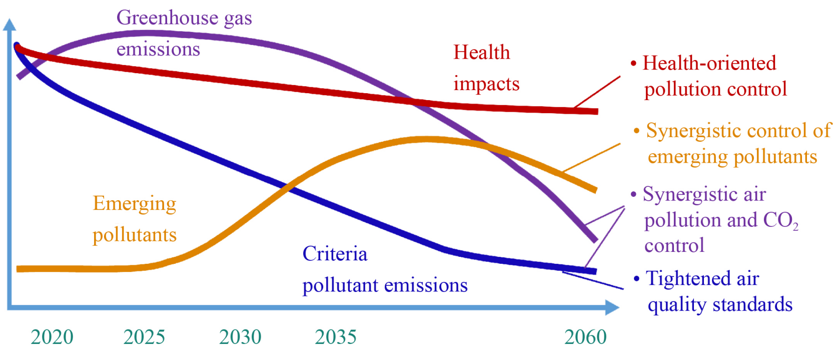
- Major challenges of air pollution control in China are summarized.
- A "health-oriented" air pollution control strategy is proposed.
- Directions of air quality standard amendments are discussed.
- "One-atmosphere" concept shall be adopted to synergistically address multiple issues.

ARTICLE INFO

Article history:
Received 7 February 2024
Revised 24 March 2024
Accepted 25 March 2024
Available online 20 April 2024

Keywords:
Air pollution
China
Health impact
Air quality standards
GHGs
Emerging pollutants

GRAPHIC ABSTRACT



ABSTRACT

Air pollution is one of the most challenging environmental issues in the world. China has achieved remarkable success in improving air quality in last decade as a result of aggressive air pollution control policies. However, the average fine particulate matter ($PM_{2.5}$) concentration in China is still about six times of the World Health Organization (WHO) Global Air Quality Guidelines (AQG) and causing significant human health risks. Extreme emission reductions of multiple air pollutants are required for China to achieve the AQG. Here we identify the major challenges in future air quality improvement and propose corresponding control strategies. The main challenges include the persistently high health risk attributed to $PM_{2.5}$ pollution, the excessively loose air quality standards, and coordinated control of air pollution, greenhouse gases (GHGs) emissions and emerging pollutants. To further improve air quality and protect human health, a health-oriented air pollution control strategy shall be implemented by tightening the air quality standards as well as optimizing emission reduction pathways based on the health risks of various sources. In the meantime, an "one-atmosphere" concept shall be adopted to strengthen the synergistic control of air pollutants and GHGs and the control of non-combustion sources and emerging pollutants shall be enhanced.

China has achieved remarkable success in controlling air pollution in the past ten years. From 2013 to 2022, the concentration of fine particulate matter ($PM_{2.5}$) in 74 key cities in China has continuously decreased from 72 μg/m^3 to 30 μg/m^3, with a cumulative reduction of 58%. This accomplishment, occurring along with rapid economic development, is hailed as the "China miracle" for the swift improvement in air quality. However, in 2022, there were still 25% of Chinese cities with $PM_{2.5}$ concentrations higher than 35 μg/m^3 and could not attain the National Ambient Air Quality Standards (NAAQS) (Ministry of Ecology and Environment of China, 2023). The average $PM_{2.5}$ concentration in China in 2022 was still approximately six times higher than the World Health Organization (WHO) Global Air Quality Guidelines (AQG). Furthermore, On the contrary, the 90th percentile of the maximum 8-h average (MDA-8) of ozone (O_3) remained at high levels of 137–148 μg/m^3

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Special issue—Towards a pollution-free planet

during 2017–2022. Identifying the key challenges in furthering air quality improvement and determining coping strategies are crucial for achieving the goal of a “Beautiful China.”

1 Challenges ahead

1.1 Air pollution poses severe threats to public health in China

Despite significant improvement in air quality in China, long-term exposure to $PM_{2.5}$ and O_3 was still responsible for about 1.34 million premature deaths in 2021, of which $PM_{2.5}$ is the key contributor (Lei et al., 2024). Moreover, the aging population in the future may to a large extent offset the health benefits brought by air pollution control. For example, Liu et al. (2022) showed that in the scenario that tracks China’s current national determined contribution (NDC) pledge and uses the best available pollution control technologies, $PM_{2.5}$-related deaths in China would almost stay the same from 2015 to 2050. This implies that more stringent control strategies must be adopted to effectively protect public health. Additionally, many studies showed significant health risks of $PM_{2.5}$ even at low concentration levels (below 10 μg/m^3), and the health risks per unit of $PM_{2.5}$ concentration can be even higher at lower levels (Strak et al., 2021; Weichenthal et al., 2022); this further amplifies the emission reductions needed to protect public health adequately.

In addition to outdoor air pollution, indoor air pollution (IAPs), including household solid fuel combustion, cooking fumes, secondhand smoke, and indoor chemicals, can pose serious health risks due to high inhalation efficiency (Zhao et al., 2018; Hu et al., 2022). For instance, household solid-fuel use was estimated to be responsible for about 680 thousand premature deaths in China in 2017 (Zheng, 2021). Despite the clean heating renovation in northern China since 2017, about 150 million tons of bulk coal (62% of that in 2017) was still used in Chinese households in 2021 (Institute of Energy of Peking University, 2023). For urban areas, Hu et al. (2022) estimated that indoor sources including cooking and second-hand smoke contributed 394 thousand (323−457) deaths in 2019, about 55% of the total $PM_{2.5}$-related deaths [711 thousand (584−823)]. IAPs rank third among all risk factors, and the rank of ten targeted IAPs in order of their contribution to disability-adjusted life years (DALYs) in 2017 was $PM_{2.5}$, carbon monoxide, radon, benzene, nitrogen dioxide, ozone, sulfur dioxide, formaldehyde, toluene, and p-dichlorobenzene (Liu et al., 2023a).

1.2 Current NAAQS are insufficient to drive further improvement in air quality

Air quality standards are an effective tool for air quality management. China released its first set of NAAQS (GB3095-82) in 1982, and revised it 1996 and 2012, respectively. The current NAAQS (GB3095-2012) has played a significant role in propelling the rapid improvement of air quality in China since 2013. In 2022, 63% of 339 major cities in China attained the NAAQS, with 75% cities achieving compliance in $PM_{2.5}$ concentration and 73% in O_3 concentration (Ministry of Ecology and Environment of China, 2023).

With most cities attaining the NAAQS, the current NAAQS is insufficient to drive rapid improvement of ambient air quality. As shown in Fig. 1, China’s current standards remain much more lenient than the WHO AQG and the standards of major developed countries (Song et al., 2024). First, China’s NAAQS are relatively loose. For example, China's standards on annual mean concentration of $PM_{2.5}$ and MDA8 O_3 are set at 35 and 160 μg/m^3, respectively, which are significantly higher than the WHO AQG (5 and 100 μg/m^3) and that of most developed countries (10–25 μg/m^3 and 100–160 μg/m^3). Secondly, China's current attainment assessment methods are also relatively lenient. For instance, in the assessment of O_3 annual compliance in China, the 90th percentile of the annual MDA8 is used, which is more lenient compared to the 93th–99th percentiles used by the WHO and major developed countries. Furthermore, the latest WHO guidelines introduced a peak-season O_3 indicator based on mounting evidence linking long-term ozone exposure to all-cause mortality and respiratory disease mortality, whereas China’s standards have not yet included indicators of long-term O_3 exposure. Therefore, tightening the NAAQS is imperative to drive continuous air quality improvement in China, especially to achieve the “Beautiful China” goal by 2035.

1.3 China needs to tackle multiple pollution issues in “one atmosphere”

China has carried out aggressive end-of-pipe control measures in key sectors. For example, by the end of 2021, 1.03 billion kW of coal-fired power units (93%) had completed ultra-low emission retrofits, making their emission levels comparable to those of gas-fired power plants. The China VI standards for light-duty gasoline and heavy-duty diesel vehicles were implemented nationally on July 1, 2020 and July 1, 2021, respectively (Lei et al., 2024). Additionally, measures such as phasing out outdated production capacity and eliminating old vehicles have been extensively implemented. With the widespread implementation of air pollution control measures, the emission reduction potential of end-of-pipe control is gradually exhausted and there are increasing challenges in further emission reductions.

At the same time, China is facing big challenges to achieve aggressive goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. China’s

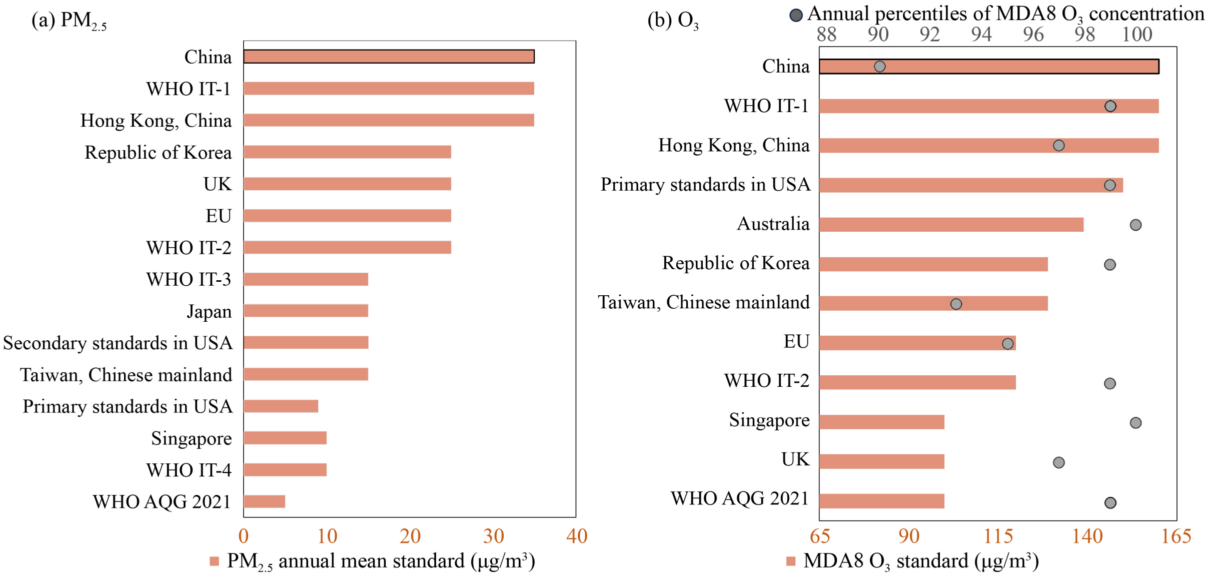

Fig. 1 Comparison of current NAAQS in China and the WHO AQG and that of other countries.

peak carbon emissions are much higher than that of developed countries/regions such as the United States and the European Union, while the time window for China to reach carbon neutrality is notably shorter. Further substantial reduction of air pollutants and achieving dual carbon goals both rely on the widespread promotion of low-carbon measures, including the expansion of new energy generation, technical innovation of industrial processes, and the adoption of new energy vehicles. However, renewable energy and green technologies also have environmental impacts, some of which are significant. Exploring optimal pathways to maximize the synergies between carbon and pollution reduction has become an urgent scientific and policy challenge.

In addition to energy-related sources, non-combustion sources such as solvent use and agriculture also have significant contributions to $PM_{2.5}$ and O_3 concentrations (Gu et al., 2018; Zheng et al., 2024). The scattered and fugitive nature of these sources greatly increases the difficulty of emission control. Currently, their emissions in China have not seen a significant reduction, requiring the development and implementation of effective control measures (Li et al., 2023). In addition to criteria air pollutants and greenhouse gases, emerging pollutants, such as emerging organic compounds and heavy metals (Jose Barroso et al., 2019; Enyoh et al., 2020; Liu et al., 2023b), need to be synergistically addressed in future control strategies given increasing public concerns about their health risks.

2 Future perspectives

In light of the challenges China is facing, it is crucial to implement "health-oriented" air pollution control strategies and tighten the air quality standards (Fig. 2). In terms of control measures, the optimal pathways for synergistic reduction of air pollutants and greenhouse gases (GHGs) should be explored and implemented. The control of non-sources and reduction of new pollutants above-mentioned shall also be enhanced simultaneously.

2.1 To implement a "health-oriented" air pollution control strategy

Historically, practices in air pollution control have predominantly focused on overall emission reductions. Moving forward, the optimization of precise emission reduction strategies necessitates a comprehensive consideration of health impacts. At national level, the premature deaths caused by air pollution are mainly attributed to $PM_{2.5}$, which shall be the key focus of air pollution control in China over the next decade. Considering the substantial differences in inhalation efficiency from various sources, systematic assessments of population exposure to pollutants should be conducted in the future. Based on these assessments, the impacts of various control measures on population exposure and health endpoints should be quantified, serving as a crucial basis for selecting preferred control measures. For indoor sources with disproportionately high inhalation efficiency, further reinforcement of control measures is necessary. This may include expanding the regional coverage of clean heating with concurrent promotion of clean cooking fuels, and enhancing the efficiency of fume purification in commercial restaurants and residential kitchens.

Previous epidemiological studies revealed different health effects of $PM_{2.5}$ from distinct sources. Some other studies analyzed the toxicity (oxidative stress,

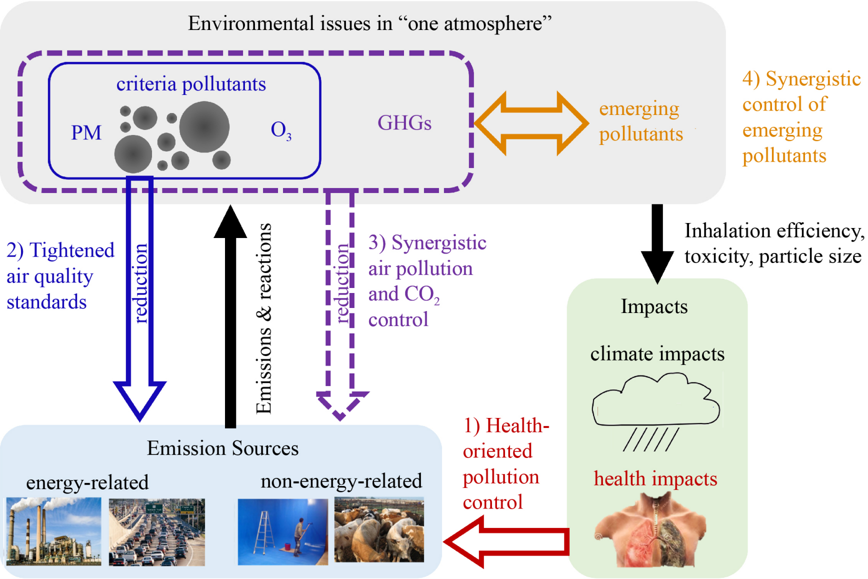

Fig. 2 Future perspectives of China's air pollution control strategies.

cytotoxicity, etc.) of particles emitted from combustion sources and industrial sources (Wu et al., 2022; Henneman et al., 2023; Wu et al., 2023). There are also studies analyzing the toxicity and health impacts of different chemical components of atmospheric particulate matter (Pye et al., 2021; Xue et al., 2021). However, the exposure-response relationships for specific sources or components are still highly uncertain.

Particle size is also a crucial factor determining its health effects, with research indicating that the health impact per unit for ultrafine particulate matter ($PM_{0.1}$) is stronger than that for $PM_{2.5}$ (Ohlwein et al., 2019; Schraufnagel, 2020). Sources of $PM_{0.1}$ include both primary emission sources like vehicles and more complex secondary processes, such as new particle formation and growth (Abdillah and Wang, 2023). Future studies are needed to establish the quantitative linkage between particle components/size and the health impacts, and to reduce the inherent uncertainty. Subsequent research should be conducted to comprehensively apportion the sources of the health impacts of particles, taking into account the differences in inhalation efficiency, toxicity of various components, and particle size. Decision makers can initially prioritize factors with lower uncertainty, such as inhalation efficiency, and as our quantitative understanding deepens, gradually consider other factors like chemical components and size. The ultimate goal is to accurately identify the most effective control measures for reducing the health impact of particles, thus achieving the maximum health benefits with the minimum cost.

2.2 To amend air quality standards for further promote air quality improvement

To achieve sustained improvement in air quality, it is advisable to timely and properly amend the air quality standards. Experiences can be leant from the United States. For example, the United States Environmental Protection Agency (US EPA) set up its primary (health-based) annual $PM_{2.5}$ standard of 15 $\mu g/m^3$ in 1997, tightened the standard to 12 $\mu g/m^3$ in 2012, and further proposed a revision of 9–10 $\mu g/m^3$ in 2023. By recognizing the significant disparity between China's $PM_{2.5}$ concentration standards and the WHO AQG, the concentration limits for $PM_{2.5}$ need to be tightened. The WHO IT-2 (25 $\mu g/m^3$) can be considered as the revised annual $PM_{2.5}$ concentration standard by 2030 considering that the current $PM_{2.5}$ levels are 30 $\mu g/m^3$ and most Chinese cities are aiming to attain 35 $\mu g/m^3$ the by 2027. Aiming at WHO AQG by 2060, China may tighten its annual $PM_{2.5}$ standard to 15 $\mu g/m^3$ in 2040 and 10 $\mu g/m^3$ in 2050, respectively. Additionally, the peak-season O_3 indicator may be included to reflect the health impacts of long-term O_3 exposure. Regarding the percentiles used in the annual attainment assessment of daily concentrations, employing higher percentiles is conducive to including more pollution days in the assessment, whereas previous studies have indicated that excessively high percentiles may intensify the impact of inter-annual meteorological variations on assessment results (Song et al., 2024). Therefore, a systematic study considering China's specific conditions is necessary to determine the appropriate percentile values. It may also be beneficial to consider using a three-year moving average to reduce the influence of inter-annual meteorological variations on assessment results. Furthermore, in contrast to developed countries that generally use concentrations at individual monitoring sites to determine compliance, China currently determines the compliance of a city's air quality based on the average concentration of all monitoring sites in the city. This approach does not adequately reflect spatial variations in air quality. In the future, it is advisable to provide both citywide averages and individual site assessment results to offer more precise support for air quality improvement.

Considering the significant regional differences in air quality across China, it is beneficial to develop local air quality standards in regions where air quality has well attained the NAAQS. Recent studies have proposed draft local air quality standards for Shanghai and Hainan (Kan et al., 2023; Song et al., 2024). For example, Song et al. (2024) proposed world-class local air quality standards for Hainan and conducted studies on the feasibility and health benefits of achieving these standards. However, further systematic research is needed to support the development of local air quality standard system and the implementation of comprehensive policies for air quality attainment.

2.3 To explore optimal pathways for synergistic reduction of air pollutants and GHGs

Our recent study has revealed that, to meet 10 μg/m^3 for annual $PM_{2.5}$ and 60 μg/m^3 for peak season O_3, China at least needs to reduce its emissions of SO_2, NO_x, NH_3, VOCs, and primary $PM_{2.5}$ by more than 95%, 95%, 76%, 62%, and 96% respectively, on the basis of 2015 (Jiang et al., 2023). Such emission reductions cannot be achieved by end-of-pipe controls. China's "dual carbon" goals will act as a powerful driver for air pollution control after 2030. Many studies have explored the co-benefits of carbon neutrality on air quality improvement. Generally speaking, carbon neutrality requires that the non-fossil share of China's primary energy consumption grows to 80–90%, which will diminish emissions of SO_2, NOx, and primary $PM_{2.5}$. Achieving carbon neutrality could synergistically reduce over half of the $PM_{2.5}$ concentration compared to a scenario that considers only the carbon peaking target (Cheng et al., 2023). Achieving carbon neutrality is a prerequisite for realizing the goal of a "Beautiful China."

However, the optimal pathways for synergistic reduction of air pollutants and GHGs are still not clear. Different control measures show distinct differences in various indicators, such as the abatement cost, the emission reduction potential of air pollutant and GHGs, the associated health, ecological, and climate impacts, and the synergy between reductions of pollutants and GHGs. For example, the electrification of trucks can simultaneously reduce CO_2 and air pollutants, but the limited mileage of electric trucks constrains their application scenarios and also increases costs. Carbon capture, utilization, and storage (CCUS) technology can significantly reduce CO_2 emissions, but it may introduce additional pollutant emissions due to increased energy consumption, and the overall costs are relatively high. There is an urgent need to comprehensively consider the above indicators and explore the most optimal technological pathway for air pollution and GHG reduction that offers a high benefit-cost ratio, good synergy, and high technology reliability. In particular, for achieving carbon neutrality and "Beautiful China," a global optimization of reduction pathways is required, considering different energy/transport/industrial/land use structures and various technological choices.

Regions and cities serve as the main entities for the implementation of air pollution and GHG control policies. However, there is currently insufficient research on detailed air pollutant and GHG reduction pathways at the regional and city levels, and there is a lack of coordination among the reduction pathways at different scales. Currently, almost all provinces, regardless of their economic structure, have set the target of reaching the carbon peak before 2030. This is not conducive to the optimization of resource allocation. Research on methodological framework and key techniques is essential to support the multi-scale coordinated control of air pollution and GHGs. This includes but is not limited to, the accurate and dynamic accounting of facility-level GHG and pollutant emissions, the integrated multi-scale modeling of the economy-energy-earth system, and a smart decision-making platform for synergistic regulation of air pollution, CO_2, non-CO_2 GHGs, and resource utilization. Both national and local technical pathways to achieve air quality and GHG reduction goals shall be explored to support the high-quality societal and economic development.

2.4 To enhance the control of non-combustion sources and emerging pollutants

Non-combustion sources cannot be effectively controlled via the implementation of low-carbon measures and may become increasingly important under the context of the "dual carbon" goals. Industrial processes and solvent use have become the largest emission sources of volatile organic compounds (VOCs) and intermediate-volatility organic compounds (I/SVOCs) and a leading contributor to secondary organic aerosol (SOA) in China (Chang et al., 2022). It is essential to fundamentally transform the structure of solvent products by developing and accelerating the promotion of low-solvent or solvent-free products. Agriculture is the largest source of NH_3 emissions and one of the most challenging sectors for emission control (Li et al., 2023). It is necessary to study and implement practical technological measures, such as balanced N fertilizer application and improved management, as well as optimized livestock production system with feeding and manure management (Zhang et al., 2020), to achieve collaborative reduction of NH_3 with greenhouse gases like CH_4 and N_2O. Strengthened controls of NH_3 and non-energy related VOCs can help most Chinese cities to meet WHO AQG for $PM_{2.5}$ up to a decade earlier than the carbon neutrality pathway.

Furthermore, the implementation of air pollution and GHG reduction measures may lead to increased emissions of some emerging pollutants, bringing about new environmental risks. For example, electric vehicle batteries contain cobalt, manganese, and nickel, which are toxic and do not degrade on their own (Mrozik et al., 2021). Also, lithium-containing compounds in battery electrolytes can be hydrolyzed in the air to produce phosphorus pentafluoride, hydrogen fluoride, and other harmful substances, contaminating the air, soil, and water (Mrozik et al., 2021). For another example, the promotion of photovoltaic systems results in emissions of heavy metals like cadmium, lead, nickel, and mercury (Tawalbeh et al., 2021). Additionally, the CCUS technology that is anticipated to be widely promoted often utilizes organic amines such as alkanolamines and piperazines as solvents. Organic amines not only serve as crucial precursors for the formation of new particles in polluted areas but can also directly pose a threat to human health by generating toxic substances such as nitrosamines and nitramines through atmospheric reactions (Nielsen et al., 2012; Yao et al., 2018). Once the above issues occur on a large scale, they may not only cause significant health and ecological damage but also prove exceptionally challenging to address due to the lack of mature technological solutions.

Criteria air pollutants, GHGs, and emerging pollutants are closely interconnected. They can be either reduced or enhanced by a given set of control measures, resulting in either synergy or trade-offs. Additionally, they interact within the atmosphere through physical and chemical processes. Traditional strategies that tackle these environmental issues one at a time may mitigate one issue while exacerbating others. Therefore, a "one-atmosphere" concept shall be adopted to synergistically address multiple issues of criteria air pollutants, GHGs, and emerging pollutants. This requires a systematic science approach to seek a "global optimal solution," which means identifying the optimized combination of control strategies to address these issues simultaneously. With regard to emerging pollutants, priority should be given to reducing the production of the pollutants at the source, while also establishing robust recycling and disposal systems to prevent harmful substances from entering the environmental media. Implementing an extended producer responsibility system that incorporates the costs of recycling and disposal into product costs is essential, with the ultimate aim of minimizing secondary risks while achieving air pollution and GHG reduction goals.

Acknowledgements This work was supported by the National Natural Science Foundation of China (No. 22188102) and the National Key R&D Program of China (No. 2022YFC3702905). We also thank the support from Tsinghua-TOYOTA Joint Research Center.

Conflict of Interests Jiming Hao is an advisory board member of *Frontiers of Environmental Science & Engineering*. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Jiming Hao is a Professor in School of Environment, Tsinghua University, Academician of the Chinese Academy of Engineering and Foreign Academician of U.S. National Academy of Engineering. He earned a B.S. from Tsinghua University in 1970, a M.S. from Tsinghua University in 1981, and a Ph.D. from the University of Cincinnati in 1984. Prof. Hao's major research interests are energy and the environment, air pollution control, greenhouse gas reduction and circular economy. He led the designation of China's acid rain control measures, developed the methodology of urban vehicle pollution control planning, and pushed the process of China's vehicle pollution control. He also developed theories and technical strategies for improving air quality in megacities and promoted the joint regional air pollution control in China. Prof. Hao is the Dean of the Research Institute of Environmental Science and Engineering, Tsinghua University and the Director of Beijing Laboratory of Environmental Frontier Technologies. He serves as the Member of the International Council on Clean Transportation, Member of the National Ecological Environment Protection Expert Committee. He also holds the additional role of Chair of the Science Advisory Committee on Air Pollution Control in the Asia-Pacific region for the United Nations Environment Programme (UNEP).