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Linking urbanization and air quality together: A review and a perspective on the future sustainable urban development

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ABSTRACT

Urbanization is one of the major transformations, along with industrialization and economic development, profoundly impacting human society and its living environment. Among the environmental elements, air quality is one of the most intuitively perceived. Most low- and mid-income countries currently suffer from air pollution, especially in urban areas. This review therefore examined the history of air pollution under different stages of urbanization in typical high-, mid-, and low-income countries and summarized the general understanding of the relationship between urbanization and air pollution to suggest the future development of the trade-off between urbanization and air pollution. Based on the review, we highlighted that the development of precautionary measures against environmental pollution during the process of urbanization. In particular, adequate attention and efficient local practices to control air pollution before the onset of heavy pollution, and local practices for multi-stakeholder satisfaction would allow sustainable urbanization with favourable air quality. We hope this review will provide powerful examples of countries that have considered and acted to balance urbanization and air quality in recent centuries, and thus serve as a reference for countries to design more appropriate actions to fulfil the 11th Sustainable Development Goal of the United Nations (UNSDG).

1. Introduction

Cities are the centres of human social economic activity. With the advancement of science and technology under the development of human civilization, the lifestyle and livelihoods of urban residents have been simultaneously modified (Boone et al., 2014; Pickett and Zhou, 2015). Starting from the appearance of ancient primitive settlements and continuing until the boom of modern cities and urban mega-regions, cities have increased in both number and size. Meanwhile, the functions of cities have increasingly become richer and more diverse (Grimm et al., 2008). However, the global urbanization process has not been uniform throughout time; cities in high-income countries, e.g., the United States and European counties, have finished rapid urbanization processes and reached high levels of urbanization. In contrast, the cities in mid- and low-income countries, which account for 90% of the global urbanization process (United Nations, 2018; Shen et al., 2016), are about to start the urbanization process, and those countries already have giant megacities such as Beijing, Jakarta, Delhi, Manila, etc. Urbanization could shift the energy structure, demand and consumption, economic growth, and political stability of environmental management and thus change environmental quality, e.g., air quality (e.g. Al-Mulali et al., 2015; Al-Mulali and Ozturk, 2015; Shahbaz et al., 2017; Ozturk, 2015). The understanding on the development and environmental quality has long been practiced, illustrated, and validated with the classical environmental Kuznets curve. The curve provides initial evidence that using an inverted-U shape characterizes the relationship between per capita emissions and per capita incomes (Stern et al., 1996; List and Gallet, 1999; Dinda, 2004; Brajer et al., 2011; Ozokcu and Ozdemir, 2017). Such factors or drivers are enough for factor-based analysis but may lose phenomenon understandings, as the protracted legal, social and political processes could also impact pollution emissions (Parrish and Stockwell, 2015). Thus, it is essential to understand the trade-off between

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urbanization and air quality by a reviewing air pollution during urbanization.

Urbanization over a relatively short period has not only improved the material wealth and lives of urban residents, but has also caused serious urban and regional environmental problems, e.g., air pollution, due to intensive human activity (Han et al., 2014). Such development was especially true after the 1760s, when modern industrialization started. Environmental degeneration was highly attributed to urban development with immoderate expansion and consumption of natural resources, especially fossil fuel consumption (Dominici et al., 2010; Han et al., 2018). Especially urban and regional air pollution, which includes pollutants such as particles, sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), and carbon monoxide (CO). Urban and regional air pollution have reduced meteorological visibility, created public health threats, and reduced urban/regional socio-economic, ecological and environmental sustainability as a whole (Hyslop, 2009; Pope and Dockery, 2012).

Currently, air pollution, which is associated with rapid urbanization and economic development, is one of the major challenges in public health, and has been listed as one of the most important contributors to the global burden of disease (GBD, 2015 Risk Factors Collaborators, 2016; Cohen et al., 2017). Although many countries globally monitor air quality and take measures to ease air pollution, only 12% of the global population lives in cities that meet the air quality standards of the World Health Organization (WHO). Air pollution is also having an extremely unbalanced spatial distribution (e.g., van Donkelaar et al., 2015). High-income countries that have completed the rapid urbanization and economic development processes have been shown to have better air quality. However, mid- and low-income countries have been undergoing or are moving towards rapid urbanization and economic development, which could threaten air quality. Thus, attention to reaching a deep understanding of the trade-off between urbanization and air pollution is essential for suggesting a sustainable development strategy, especially for most mid- and low-income countries.

Air pollution is a long-standing and complex issue that accompanies the processes of urbanization, and intensive human activities have occurred throughout human history, especially after the 18th century (Bai et al., 2017). Urbanization progressed very slowly before the 18th century, because people could hardly survive without farmland. The air quality degeneration in this period mainly occurred at the local scale and/or during a short period. The major causes of air quality changes were natural phenomena, e.g., strong winds create dust storms in drylands, and volcanic eruptions make ash clouds. However, very few cases of air quality degradation were driven by human activities, e.g., traditional slash-and-burn farming and improper use of fire, which incidentally cause fire accidents in natural ecosystems and decrease the air quality (Han and Zhou, 2019). These changes in air quality can be assumed to have still been within the self-purification ability of the natural ecosystem. However, during and after the 18th century, the air quality degeneration changed from local and/or short spatiotemporal scales to regional and/or long spatiotemporal scales because of the revolution in energy usage and the rapid growth of modern cities. As early as the late 18th century, the rapid expansion of steam power caused large increases in coal consumption in the increasingly population-dense industrial cities from England to West Europe, North America and to the rest of the world (McNeill, 2000). Coal-burning air pollution thus spread throughout the world due to the Industry Revolution, which introduced rapid population gathering in industrial cities. Although Word Wars I and II somewhat slowed industrial urbanization, gathering the core burning industries in cities finally caused the severe air quality degeneration in the 1960s. However, the air pollution in this period was not well recognized or understood by the majority of both the authorities and the public, who even identify pollution as a symbol of development (Fenger, 2009). With the rapid progress of petroleum exploitation and petrochemical technologies in the middle of the 20th century, the coal-based energy structure began to shift to a coal- and petrol-based energy structure. Meanwhile, urbanization was accelerated by the increasing labour needs, expanding industrial areas and high-density populations in urban areas. These changes also caused the shift from coal-burning air pollution to coal-burning and petrol-consumption mixed air pollution, which was more complex than the pollution in the previous situation. Coincidentally with the petrol-based revolution, air pollution was gradually realized by authorities and the public through the literature, scientific research, and especially notorious environmental crises, e.g., the London fog and Los Angeles smog. Those factors promoted public awareness of pollution and pushed authorities to improve air quality. Within the half-century until the end of the 20th century, major high-income countries have effectively restored urban and regional air quality through regulations design and implementation. However, the vast number of mid- and low-income countries on the planet have just started economic, and urbanization development and are predicted to experience air pollution in the future if they follow the traditional development strategy, as most high-income countries have done. Their air pollution may be even more severe and complex than that in the history of high-income countries, as their development would mix coal-burning, petrol-based, and other new types of air pollutants (e.g., Han et al., 2018). Thus, the strategy of considering the trade-off between the economy and urbanization and air pollution became an urgent but not new issue for those countries.

Research on the trade-off between urbanization and air pollution is outdated in the high-income countries as those countries have finished rapid urbanization and improved air quality after a severe pollution history compared with mid- and low-income countries. However, the relationship between urbanization and air pollution is still unclear in mid- and low-income countries and covers complex fields in the 21st century with rapid science and technological innovation and upgrades. As air pollutants could directly impact public health, the identification and assessment of air pollution-induced health impacts have long been examined in the fields of medicine and atmospheric chemistry as well as through some cutting-edge multidisciplinary studies (e.g., Cohen et al., 2017; Brunekreef and Holgate, 2002; Nriagu and Pacyna, 1988; Han et al., 2014). Some preliminary studies have concentrated in the spatiotemporal patterns of air pollution in urban and non-urban areas, the contribution of urbanization-induced population migration to public air pollution exposure, and the relationships between urban air quality, and urban natural and socio-economic factors (Bai et al., 2017; Baklanov et al., 2016; Parrish and Zhu, 2009). However, those works have primarily considered relatively short-term changes on the diurnal, monthly, annual or decadal scales for country-specific cases, but lack in comprehensive review and examination among typical countries with urbanization and air quality. Therefore, the objectives of this review were 1) to examine the history of air pollution under different urbanization stages in typical high-, mid-, and low-income countries, 2) to summarize the general understanding of the relationship between urbanization and air pollution, and 3) to suggest future developments in the trade-off between urbanization and air pollution, especially for mid- and low-income countries that are undergoing or have undergone rapid urbanization and the predicted air pollution. We hope this review will provide strong examples of the views and actions of countries on urbanization and air pollution in recent centuries, and thus serve as a reference for countries to design more appropriate actions towards better fulfilling the 11th Sustainable Development Goal of the United Nations (UNSDG) (Fig. 1).

2. Global urbanization and air pollution in the recent centuries

Differences in economic development, science and technology levels, location and historical characteristics have created diversity in the urbanization stage and its accompanying air quality (e.g. Gollin et al., 2016). Against the urbanization process, air pollution in high-income countries reached a peak in the middle of the 20th century. Mid- and low-income countries started to realize and ease air pollution at the end

Fig. 1. A frame to correlate the 11th UNSDG with the trade-off between urbanization and air quality.

of the 20th century and the beginning of this century (McNeill, 2000). The way that low- and mid-income countries develop, especially in their understanding on the trade-off between urbanization and air quality, will shift and form global air quality (e.g., China, Han et al., 2015). Thus, examining and summarizing the diverse trade-off processes between urbanization and air quality would provide additional insight.

In this review, four groups of counties were selected with considering the differences in both their urbanization processes and air quality changes (Fig. 2). Type I, which included the United Kingdom, Germany, and France, illustrated the urbanization and air quality processes from early industrialization to the present day in Europe. Type II, which included the United States and Canada, illustrated the air quality and urbanization processes in industrialized counties in North America. Type III, which included Japan and Singapore, illustrated the air quality and urbanization processes in the newly industrialized Asian countries. Type IV provided insight into South Africa, Brazil, China, and India to illustrate of air quality and urbanization prodesses in mid- and low-income countries. The urbanization processes and the major policies and activities of these countries on air pollution/quality management were examined and analysed (Fig. 3). Details of each country followed.

2.1. The United Kingdom: an industrialization pioneer with a nearly century-long history in air pollution control

The 150-year development of the United Kingdom (UK) after the Industry Revolution highlighted development, while reducing coal consumption and promoting technological improvement. Such development could reduce carbon dioxide emissions and improve public health conditions, demonstrating the first country to cut the per-capita emissions compared to 1860s level (e.g. long span cutting-edge econometric modelling results in Hendry, 2020). Meanwhile, Air pollution in the UK closely accompanied industrialization and urbanization; however, public attitudes on pollution were contentious. As early as the 13th century, improvement in transportation promoted widespread coal consumption in the UK, but soot pollution did not attract attention from either the public or the authorities (Brimblecombe, 1978, 2003). In the following centuries, although scientists and doctors were aware of the impact of air pollution on public health under worsening air pollution conditions, action on urban air pollution improvement did not arise through brave proposals because of the enthusiasm for urban development-induced improvement of material life well-being. After the 18th century, the literature on air pollution pushed both the public and authorities to realize the health impacts of air pollution from coal combustion, forcing legislation for air pollution prevention and control. For example, the first effective Alkali Act of 1863, which initially focused solely on the heavy chemical industry. Soon during the first Industry Revolution, the rapid spread of improper combustion of coal caused the exacerbation of air pollution (Brimblecombe, 1987). To summarize the air pollution when urbanization was below 50% in the UK, coal combustion provided a steady energy that transformed to social wealth, especially material wealth, and the negative impact of the induced air pollution was therefore subconsciously ignored and neglected.

After entering the period when urbanization grew to over 50% but below 70%, attention to pollution did not limit the development of the economy, and the rapid and substantial improvement of material well-being from urbanization nearly distracted the public from environmental problems (Chisholm, 1974). Although a very limited number of protest activities occurred during this period, the understanding of urbanization or economic development and air pollution remained in a very preliminary stage, and air pollution was often interpreted as a nonissue.

In approximately 1900, the urbanization rate exceeded 70% in the UK. The public gradually realized the negative impact of air pollution and started to fight against it (Chisholm, 1974). One of the iconic events was the *London smog*, which sickened and killed thousands of people in 1952, awaking both the public and the authorities and causing them to rethink the trade-off between development and air pollution and to

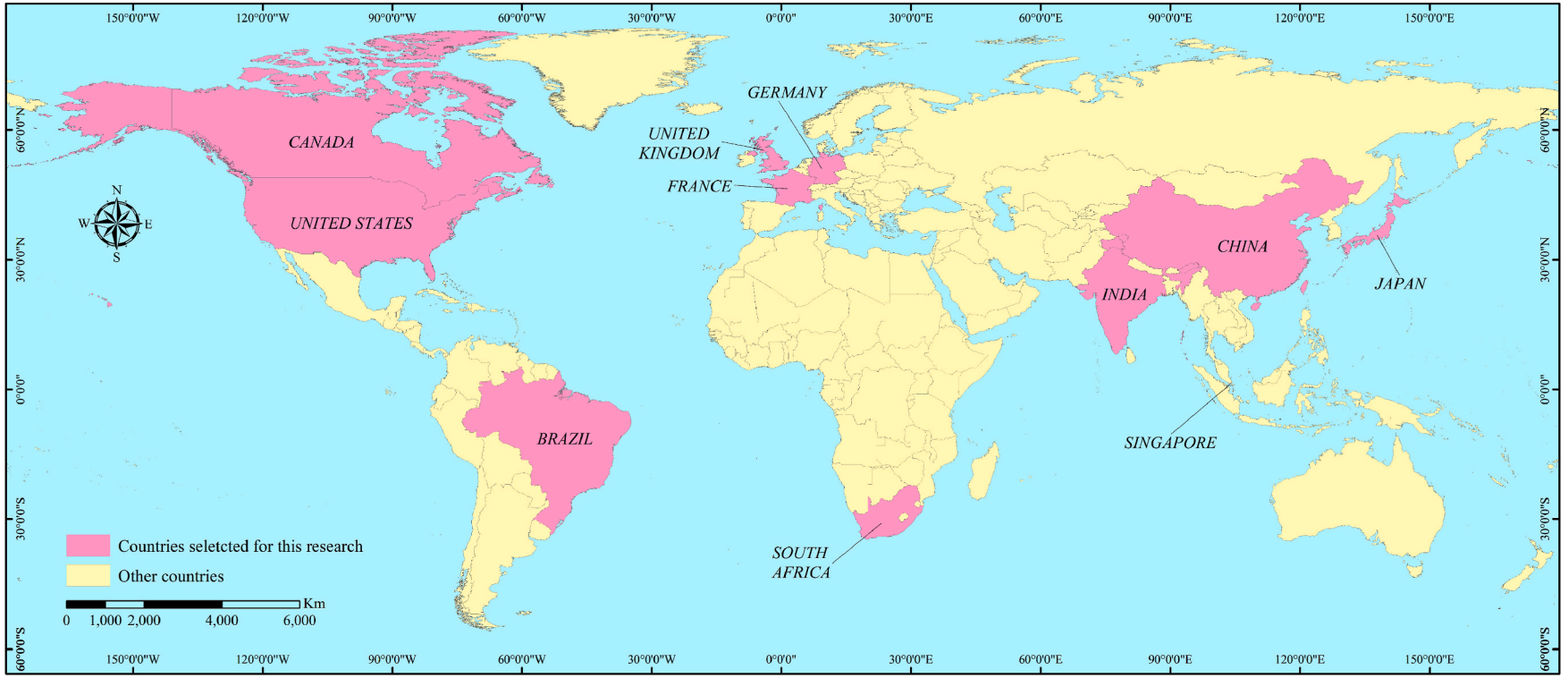

Fig. 2. Countries selected in this research to illustrate urbanization and air pollution.

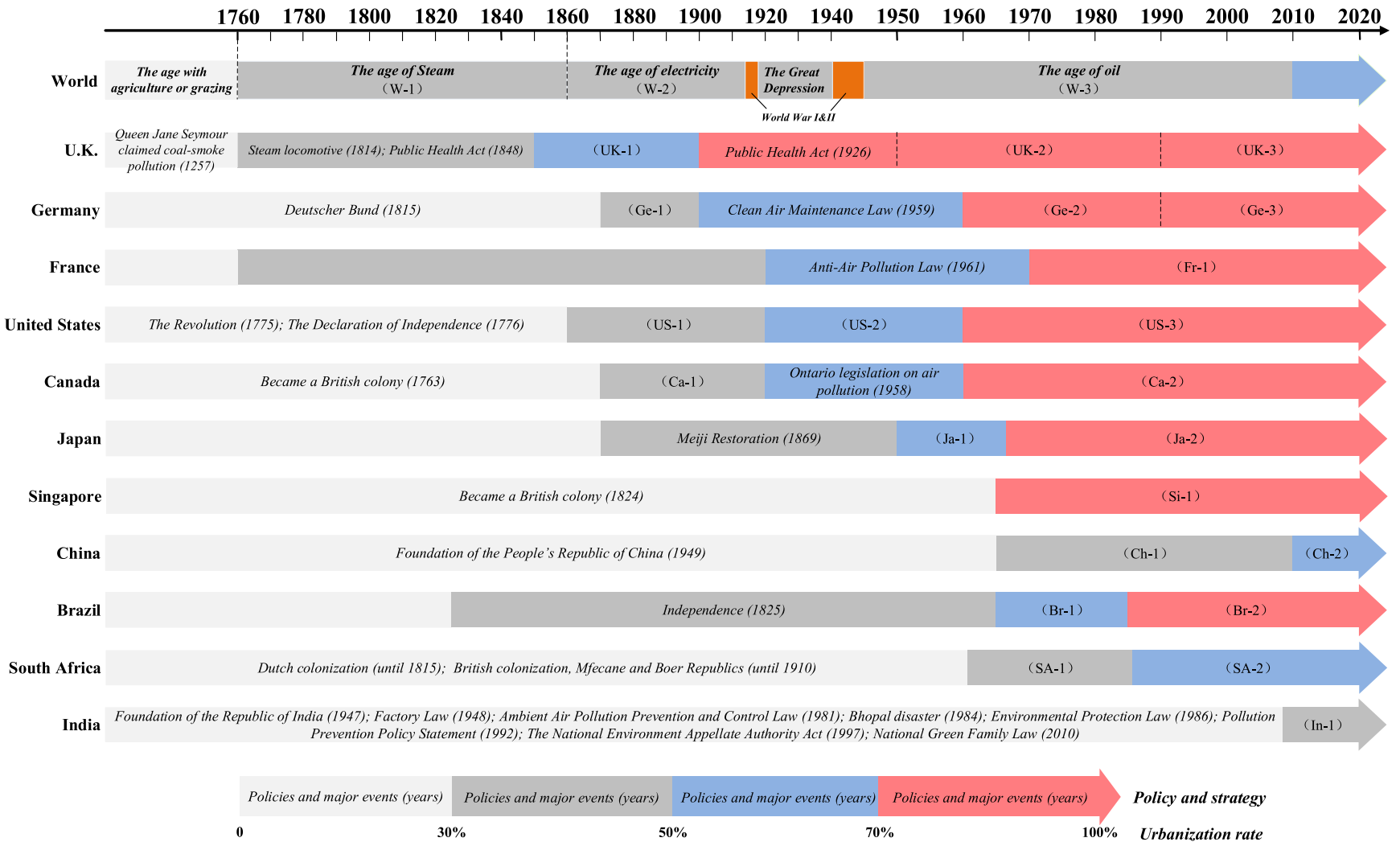

Fig. 3. Urbanization process and air pollution prevention/control policy nexus in typical countries.

Marks	Policy and strategy （year）	Marks	Policy and strategy（year）	Marks	Policy and strategy（year）
W-1	The spinning jenny invented in 1765; Invention of steam engine by Watt in 1769	W-2	Generator(1866);Electric motor (1870); Gasengine (1876); Gasoline and diesel engines (1876 and 1897)	W-3	Vienna Conventions (1985); Montreal Protocol (1989); The World Summit on Sustainable Development (1992); Kyoto Protocol (1997)
UK-1	The first case of smog induced death (1873); Akali Act (1863); Industrial Development Environmental Law (1863)	UK-2	The Great Smog of London (1952); Beaver Report on Air Pollution (1954); Clean Air Act (1956, 1968); Control of Pollution Act (1974);	UK-3	Environmental Protection Regulation (1990); Environmental Law (1995); The Air Quality Strategy for UK (1997, 2003, 2007);
Ge-1	Franco-Prussian War (1870); Trade Regulation (1869)	Ge-2	The 1st heavy pollution in Ruhrgebiet (1962); Haze Ordinance (1964); The Technical Instruction Air (1964); Federal Pollution Prevention Law (1974, 1983, 1986); Federal Exposure to Pollution Act (1974); Clean Air Plans (1975); Convention on Long-Range Transboundary Air Pollution (1979)	Ge-3	Federal Emission Control Act (1990, 1994; 2005); The right to heath is a fundamental constitutional (1993); Environmental Protection in the 21st century (1996); Gothenburg Protocol (1999); Ozone Reduction Policy (2002)
Fr-1	Ministry of Environment (1961); Environmental Law (1983); Vehicle restriction (1997); Air and Energy Rationing Act (1996); Air Quality Regulation (2010); Energy Transition for Green Growth (2015); Air Quality Certificate and Restricted Traffic Zone (2016)	Ch-1	Air Pollution Prevention Act (1965, 1987, 1995, 2000, 2014); Reform and Opening-up Policy (1978); National Environmental Protection Bureau (1988, 1998); Ministry of Environmental Protection (2008)	Ch-2	Ambient Air Quality Standard (2012); Beijing Haze (2013); Ministry of Ecology and Environment (2018)
US-1	Civil War (1861-1865); The 1st air pollution related litigation (1864); Georgia litigation on Tennessee copper industry exhaust emission (1907)	US-2	Los Angeles and Donora smog (1943, 1948); Air pollution restrict zone (1947); Air Pollution Control Act (1955)	US-3	Clean Air Act (1963, 1970, 1977, 1990); Air Quality Law (1967); Earth Day activity (1970); Establishment of the U.S. Environmental Protection Agency (1970); Ambient Air Quality Standard (1971); North American Agreement on Environmental Cooperation (1993)
Ca-1	Independence (1876); Rapid economic development (1896-1914)	Ca-2	Sudbury pollution (1971); Establishment of Environment Canada (1971); Environmental Protection Law (1988, 1999); Air Pollution and Smoke Control Ordinance (1978); Convention on Long-Range Transboundary Air Pollution (1979); North American Agreement on Environmental Cooperation (1993)	Si-1	Clean Air Act (1972); Establishment of Environmental Ministry (1972); Electronic Road Pricing System (1989); Certificate of Entitlement (1990); Green Singapore Plan (1992); Environmental Pollution Control Regulation (1999, 2008); Sustainable Singapore (2009)
Ja-1	Yokkaichi asthma (1961); Soot Emission Regulation and limitation (1962, 1964)	Ja-2	Basic Law for Environmental Pollution Control (1967); Air Pollution Prevention Act (1970, 1992); Environmental Protection Law (1971); Vehicle NOx, PM regulation (1992, 2001, 2007); VOCs regulation (2006); $PM_{2.5}$ Environmental Standard (2009)	In-1	Air Pollution Control Plan (2017)
Br-1	Basic Law for the Environment (1981);PROCONVE (1986); Environmental right into the Constitution (1988)	Br-2	The World Summit on Sustainable Development (1992); Restrict Traffic Zone (1996); PROMOT (2003)		
SA-1	Foundation of the Republic of South Africa (1961); Air Pollution Prevention Act (1965)	SA-2	Environment Conservation Act (1989); Environmental right in Constitution (1996); National Environmental Management Act (1998); Air Quality Law (2004); Department of Environmental Affairs (2009)		

Fig. 3. (*continued*).

move towards comprehensive control of air pollution (e.g. Dooley, 2002). A series of acts on pollution control and prevention, e.g., the Clean Air Act in 1956, were established and well implemented, significantly improving the urban air quality in the second half of the 1970s. After the 1970s, more comprehensive and specifically targeted acts and actions took place (see more detail policy and strategy in Fig. 3 U.K.), continuously improving the air quality (Mosley, 2001). In recent decades, attention has been given to furthering industrial pollution control and vehicle emission reduction through multi-stakeholder cooperation (Elsom, 1999; Beattie et al., 2001; Longhurst et al., 2006). Cooperation was achieved by building specialized management and advisory agencies that contain air quality related industries and promote universities, research agencies, and companies to join air pollution research and technological development. Furthermore, citizens participated and supervised air quality improvement and air pollution emission control. Such cooperation has made adopted actions well understood and accepted by the public, scientists, and authorities on air pollution control.

2.2. Germany: efficient in both urbanization and air pollution control

Germany experienced one of the most rapid economic and urban developments and has led the world in environmental policy design and practice, exemplifying as one of the most effective country models for air pollution control. The manufacturing and traffic transportation industries attracted farmers, causing them to take jobs as industrial workers and shift into industries in concentrated urban areas, resulting in an early-stage urban boom in Germany. Meanwhile, Germany established air pollution laws and regulations, e.g., the trade regulation enacted in 1869 and the technical directive enacted in 1895, which set the foundation for efficient German air pollution control. Twenty years after the establishing the German empire (1871), Germany stepped into rapid nationwide industrialization, causing the urbanization rate to reach 50%. However, the subsequent intensive development of the chemical and metallurgical industries resulted in regional ecological and environmental degeneration. For instance, heavy air pollution and acid rain occur in industrial cities (Beck, 1984). In the early twentieth century, such environmental disasters frequently occurred, pushing the country to slow down the development of heavy industries with high energy and resource consumption and high pollutant emissions. Although World Wars I & II reduced the German economy back to a pre-World War I level, the German industrial sector was well and rapidly constructed after the war (Weber, 1981).

From 1945 until 1990, Germany was divided into four zones by Americans, the British, the French and the Soviets, making the country into the Federal Republic of Germany (FRG) and the German Democratic Republic (GDR). The air pollution in the FRG and GDR could be a typical example that shows the different approaches to environmental protection and air quality management between the western and eastern blocs in Europe after World War II (McNeil, 2000; Ionata, 1991; Rink, 2002). The difference between GDR and FRG in land/population sizes and natural resources together with the economic, social and political system led to diverse industrialization, causing severe air pollution especially in GDR (Ionata, 1991; Rink, 2002). The overwhelming consumption of brown coal and low-grade gasoline in outmoded production processes without efficient environmental regulation was the major reason for severe air pollution in the GDR (Ionata, 1991). In addition, the government authority shielded polluters. It even made environmental information a state secret. The whole society's public ownership bonded the interests of citizens and state-owned pollution enterprises (McNeil, 2000), making the public's late awareness of the air pollution in GDR and other eastern blocs in Europe in the period.

Until the middle of the 1960s, Germany was one of the world's major economies, and the urbanization rate exceeded 70% (Berthold and Grundler, 2015; Vogele, 2000). Heavy air pollution reached its peak, which was recorded by environmental crises, e.g., the haze crisis in the Ruhr industrial zone and the GDR, which spurred the country to carry out efficient air pollution control (Currie, 1982; Lohrer, 1990). After the reunion of Germany in 1990, one of the significant milestones was the establishment of health as a basic right in the constitution in 1993, after several decades of action on air pollution control with intensive policies, strategies, and wellness practices (see detailed policies and strategies in Fig. 3 Germany). In recent years, in addition to updates to environmental protection laws and increased practical efficiency of the regulations and laws, air pollution control has been involved in market regulations, public engagement, cross-country cooperation, and the most important environmental technological investments (Gollata and Newig, 2017). In 2010, the formerly seriously polluted Essen in the Ruhr industrial zone was selected as the European Capital of Culture, indicating the maturation of the trade-off between development and the environment.

2.3. France: moderate air pollution with multi-party participation in air pollution control

Air pollution never reached the level of disasters like the London smog in other European countries; however, it confounded and limited urban development in France for more than a century. Before the 16th century, the urbanization rate in France was higher than that in the UK; however, the slow industrialization in France, particularly after the 19th century, caused the slower urbanization rate to reach 50% approximately 1850, eight decades later than that in the UK. However, urbanization rates from 50% to 70% have existed for approximately four decades (Thompson, 1925; Bonneuil and Rosental, 1999), one decade shorter than those in the UK. Rapid development, especially after 1946, when the French Fourth Republic was founded, caused air quality degeneration. In contrast to industrially driven air pollution in other countries, biofuel usage in low-efficiency household heating devices was one of the major causes of air pollution in the early stage of France.

By the end of the 1960s, the French urbanization rate reached 70%, and more attention was given to air pollution prevention (Slovic and Ribeiro, 2018). In the beginning, pollution prevention lacked widely accepted policies and air quality standards, resulting in only a small step forward in pollution control and prevention (Audurier-Cros, 1982). Until the act concerning the synthetic use of air and energy was enacted in 1996, which was forced by pressure from environmental protection organizations and the public in 1995, it formed the first widely accepted act in the country. From then to the present, many air pollution prevention regulations and acts, including the Air and Energy Rationing Act, Vehicle Restriction (1997), Air quality Regulation (2010), and Air Quality Certificate and Restricted Traffic Zone (2016), have been established to optimize air quality (see the detail policies and strategies in Fig. 3 France). Some typical methods of pollution control and prevention, e.g., promotion of household emissions reduction, air quality monitoring network construction, and clean energy tax refund policy (Remvikos et al., 2009), and the recent practice of air quality certification for vehicles and restricted traffic zones in approximately 2016, gradually created multi-party participation in air pollution control.

2.4. The United States: unexpected economic and urban development with expected air pollution

Air pollution in the United States lasted several long and complicated centuries, with a continuous improvement during the historical period of combined industrialization, urbanization and economic development. After the Civil War, the United States started to learn from both the experiences and the technologies of Europe, causing its rapid economic development and driving population migration into urban areas or transportation nodes, which eventually formed into megacities or urban clusters. The gathering of both populations and industries in those areas finally triggered air quality degeneration in the mid-19th century. The coal combustion-driven air pollution was finally recognized by the

authorities in this period. Acts and laws were then enacted by both federal and state governments, illustrating the early stage in the development of the U.S. towards air pollution prevention and control (Merrill, 1997; Lakhani, 1982).

In approximately 1920, the urbanization rate in the U.S. reached 50% with the support of the population and industrial concentration, and transportation network development (Long and Deare, 1983). With the need for economic development, especially reconstruction after the economic crisis, environmental protection was out of reach for both the public and authorities. This mindset continued until the 1940s, when air pollution disasters, such as the Los Angeles photochemical smog in 1943 and the Donora smog incident in 1948, woke the public to think and practice air pollution control and prevention, and led to the Clean Air Act. In particular, the construction of a set of environmental laws was the first action taken by both federal and state governments in the U.S.

The urbanization rate exceeded 70% in the 1960s, and Americans realized that air pollution would limit the development of cities and economies by threatening public health (Schueneman, 1963). Although the Clean Air Act enacted in 1963 raised the trade-off concept for both economic development and environmental quality, it was not implemented as designed due to low mandatory local execution (Senate, 2004). Until the late 1970s, after several terms of environmental law updates (see the detail policies and strategies in Fig. 3 United States), including the revisions of the Clean Air Act. The air pollution in the U.S. was then shifted to prioritizing air pollution prevention instead of the previous focus on pollution control, and air pollution control moved into air pollutant emission source control and management. Meanwhile, governmental environmental management methods also moved from administrative management to marketing-oriented strategies (Lakhani, 1982). Until the 1990s version of the Clean Air Act, the U.S. formed a well-constructed air quality management legal system along with efficient local practices. In recent years, air quality has been gradually improving due to environmental technological improvement and innovation, widely following environmental regulations, and public engagement in air quality satisfaction, e.g., citizen science (Allen, 2017; Mahajan et al., 2020).

2.5. Canada: a cautionary tale on air pollution and a success story about multi-stakeholder engagement in pollution control

The excess natural resources, especially mineral resources, and absence from the two world wars in its territory provided the opportunity for urban development that concentrated in the limited area next to the United States. The intensive development in concentrated urban areas created intensive air pollution, which has been eased by cross-industry, cross-sector, and cross-border cooperation. As early as the end of the 19th century, wheat farming-oriented economics pushed the Canadian urbanization rate to over 50% in 1920. Such agriculture-based development caused significant deterioration of the air quality during those decades (Tucker, 2010). After 1926, Canada began to develop rapidly thanks to both abundant domestic natural resources and the opportunity that arose from limited participation in World War II. The industrialization was well engaged and concentrated in limited areas in the southern part of the country next to the U.S.

These developments pushed the country's urbanization rate to 70% within 40 years by 1960. Rapid, intense, and concentrated urbanization has had a significant negative impact on the air quality of urban areas and their nearby areas (Katz and Ball, 1963). However, during the 40 years of development, air pollution and prevention in the country were based on experiences solving every air pollution emergency; however, almost no environmental legal system was developed and practised until the 1970s (Rivers, 1979). One typical city that illustrated the country's severe air pollution was Sudbury, referred to as a "*blackened moonspace from a century of smelting*". After the dark age of pollution in the 1960s, Canada implemented air pollution control and prevention in the 1970s, which was recognized as the most important decade in Canadian environmental history for air quality improvement (see the detail policies and strategies in Fig. 3 Canada). Canadians' methods constructed their suitable environmental legal system and cross the border with the U.S., which cooperated on air pollution early-warning systems, emergency management, and prevention as air pollutants easily moved across the Canada-U.S. boundary. In addition, Canada also encouraged the public to engage in air quality improvement, e.g., the famous reduce, reuse, and recycle (3R) initiative.

2.6. Japan: efficient innovations and action created good air quality

Japan experienced one of the most rapid economic and urban development processes, which resulted in heavy air pollution that threated the public health and led to one of the most efficient and intensive air pollution control regimes, forming an iconic air pollution history. The Japanese economy grew in a rapid and comprehensive way after the famous Meiji Restoration (1869). Japan had expertise in learning, applying, improving, and innovating technology as early as the Industry Revolution. Those technological innovations reorganized the economic structure and enticed the population to move into giant cities, which finally formed famous urban clusters, e.g., Tokyo-Yokohama and Osaka-Kobe, which allowed Japan to exceed urbanization rates of 50% in 1950 and 70% in 1967. Such development in a relatively short period caused significant negative impacts on the environment, causing public nuisance diseases, e.g., Yokkaichi asthma, which finally pressured both enterprises to pay attention to pollution control and prevention and the authorities to pass and implement environmental legislation.

Many air pollution regulations and laws were established in the middle of the 1960s (see the detail policies and strategies in Fig. 3 Japan), including the Basic Law for Environmental Pollution Control enacted in 1967, the Air Pollution Prevention Act enacted in 1970 and further updated in 1972 and 1974, the Environmental Protection Law enacted in 1971, and the Compensation Regulation to Health Victim of Environmental Hazard enacted in 1974. The practice of those laws and regulations brought the air quality under control at the end of the 1970s, and further created excellent air quality in Japan at the end of the 1980s (Wakamatsu et al., 2013). In addition to effective policies and regulations, within a half century, the processes of urbanization, air quality degeneration and pollution control have dramatically changed, which is highly attributed to the improvement and innovation of low energy and resource consumption and environmentally friendly technologies (Hashimoto, 1989; Baker, 2000). As a result, the nexus of the economic and urbanization processes and air pollution in Japan showed an excellent example of both rapid economic and urban development, and pollution control. However, it still followed the traditional economic and urban development method prior to pollution, and pollution forced the authorities to improve technology and tighten the restrictions for pollution control.

2.7. Singapore: efficient air pollution control caused by good cooperation among the government, enterprises, and the public

Singapore is a unique example of adjusting inner urban areas for air quality improvement through the economic boom as a city-state. After the country was founded in 1965, the labour-intensive industry pushed the country into becoming one of the famous Asian Tigers. Such intensive development caused the city's air quality to drop sharply, but strict environmental laws and regulations together with clear functional agencies for air quality management made Singapore recognized the trade-off between economic development and air quality conservation. Policies and strategies such as the Clean Air Act (1972), Electronic Road Pricing System (1989), Green Singapore Plan (1992), Environmental Pollution Control Regulation (1999, 2008) and Sustainable Singapore (2009) formed the modern air quality management system (see the detail policies and strategies in Fig. 3 Singapore). The people, public, and private (3P) worked together in support of air quality protection,

which was another way to gather multi-stakeholders in Singapore.

As a city state, the air quality of neighbouring countries is another important concern because pollutants could easily shift into the city; thus, cross-boundary cooperation on air pollution prevention is also an important task (Kusumaningtyas and Aldrian, 2016). Currently, Singapore's air quality is much better than the other large countries in Asia. However, Singapore's good air quality benefits more from the tropical climate, e.g., frequent rainfall. Air quality control and better developing way would be an additional aid in air quality satisfaction. It thus has provided an example to cities in other countries that are undergoing or will carry out rapid urbanization on the way to develop with reasonable air quality reduction.

2.8. China: severe air pollution forced uncertain efficiency of air pollution controls

China has a long history of being recognized as an ancient civilization in human history; however, the moderate development during the long feudal dynasties and the closed-door policies in the most recent Yuan and Qing dynasties caused China to "perfectly" miss the Industry Revolution. This meant that the country did not experience human-caused air pollution until the early twentieth century. Some air pollution-like events, e.g., local or regional dust outbreaks, have been recorded throughout history due to dry surfaces and strong wind blowing (Han and Zhou, 2019). In the first half of the twentieth century, China's economic and urban developments entered a period of stasis or even reduction due to its civil wars and wars with Japanese aggressors. Almost no air pollution was recorded by or attracted the attention of either the authorities or the public.

The development of modern China, the Peoples' Republic of China, started in 1949. Environmental pollution after 1949 is highly attributed to the high-intensity but the low-technology level in large amounts of fossil energy and other natural resource consumption without taking enough concerns on the environment. In the early stage from 1949 to 1979, China paid strong attention to industrial development but limited population movement and did not consider environmental protection. However, it was very lucky that human activities were not intensive enough to significantly influence air quality. From the end of the 1970s to the end of the 1990s, the famous "Reform and Opening-up (ROU)" policy started to take effect, but the country was still in a stage of moderate development. Although such development had a negative impact on the environment, it was still at the local scale and attracted very limited attention from authorities and the public. China's initial atmospheric pollution regulation was enacted in 1987 (see the detailed policy and strategy progress of China's air quality management in Fig. 3); however, it seemed that no local practices were carried out (Han and Zhou, 2019; He et al., 2002). After 2000, China started its remarkable economic development, with massive population movement into cities, which introduced intensive human activities that emitted massive and complex air pollutants without strict actions, especially at the level of local practices, on pollution control (Chan and Yao, 2008; Han et al., 2018). Thus, heavy air pollution events have frequently occurred in China, especially in areas with high population densities, industries and cities and their surrounding regions as a whole, e.g. China's Beijing-Tianjin-Hebei urban megaregion has been suffering from the one of the world's heaviest air pollution for the past several years (e.g. Han et al., 2015).

In 2011, China's urbanization rate exceeded 50% but was still less than 70% until now, and its action on air pollution control was pushed by the public, especially in some hot-spot urban aggregations, e.g., the famous Beijing-Tianjin-Hebei area and the deltas of the Yangtze and Pearl rivers (Gu et al., 2017). Although its former heavily polluted capital, Beijing, had improved air quality, the contributions of anthropogenic and meteorological reasons for the pollution improvement were not very clear since the nationwide urban air quality monitoring network (http://www.cnemc.cn/) was established recently in 2012. With the current legal system and local practices, there will continue to be uncertainty about the consistency of air pollution control until the air quality reaches a healthy level as China's urbanization rate is still below 70%, and the country is eager to realize its urban dream before 2050 or even earlier (Bai et al., 2014).

2.9. Brazil: multi-level government cooperation produces better air quality

Imbalanced economic development without adequate consideration of the environment results in heavy air pollution; however, the democratization of air pollution control and prevention effectively improved the air quality, reflecting the major characteristics of air pollution in Brazil. Since the 1960s, Brazil started its "miracle" industrialization, which was recognized as an industrial system with a complete range of production and brought incredibly rapid economic development that concentrated in cities connected by dense transport networks (Abe and Miraglia, 2016).

The urbanization rate reached 50% from the 1960s–1970s, after which Brazil began deindustrialization, which caused the country to lose focus and confidence in economic development, trapping the country in the unsustainable pattern of both environmental degeneration and economic recession until the 1980s. After the 1980s, with the country's gradual transition to democracy, many non-governmental environmental organizations were energetically involved in public health management, which simultaneously improved the efficiency of environmental protection. The Environmental Basic Law enacted in 1981 specified atmospheric pollutant environmental standards and emission baselines, which was notable in Brazil's history of air pollution control and prevention (Csillag, 2000).

As soon as Brazil's urbanization rate exceeded 70%, those environmental laws and regulations were upgraded to be more detailed and strict, e.g. set Restrict Traffic Zone in 1996 (See more policies and strategies on air quality management of Brazil in Fig. 3). Meanwhile, cleaner energy usage also greatly helped improve air quality (Geller et al., 2004). The previously heavily polluted Cubatao, once known as the Valley of Death, had greatly improved air quality (Lemos, 1998). Currently, supported by multilevel environmental governance from federal, state, and municipal agencies, both the legal system and its practice in air pollution control and prevention have been well organized and employed.

2.10. South Africa: trapped in a cycle of deindustrialization and air pollution

Development supported by the resource and energy industries but a lack of innovation and competitiveness in the technology sector created a long and tortuous path for South Africa between urbanization and air pollution. As the pioneer of industrialization and urbanization on the African continent, air pollution was concurrent with development in South Africa. The development knowledge from high-income countries and the African characteristics of South Africa gave the air pollution unique characteristics that combined air pollution from both industries and traffic systems, as seen in high-income countries, and inefficient usage of fossil fuels and biofuels in poor communities, like in mid- and low-income countries. Thus, the trade-off between urbanization and air quality was difficult to reach.

Before the urbanization rate reached 50%, South Africa established the air pollution prevention act as early as 1965, four years after the founding of the Republic of South Africa (see more policies and strategies on air quality management of South Africa in Fig. 3). However, the administration of the law was relatively inefficient and limited due to the need for both economic and urban development. After the urbanization rate reached 50% in 1986, public awareness of air pollution pushed serious actions in air pollution control and prevention, including the enactment of the environmental protection law in 1989 and practices of pollution control and prevention. However, due to the inefficient

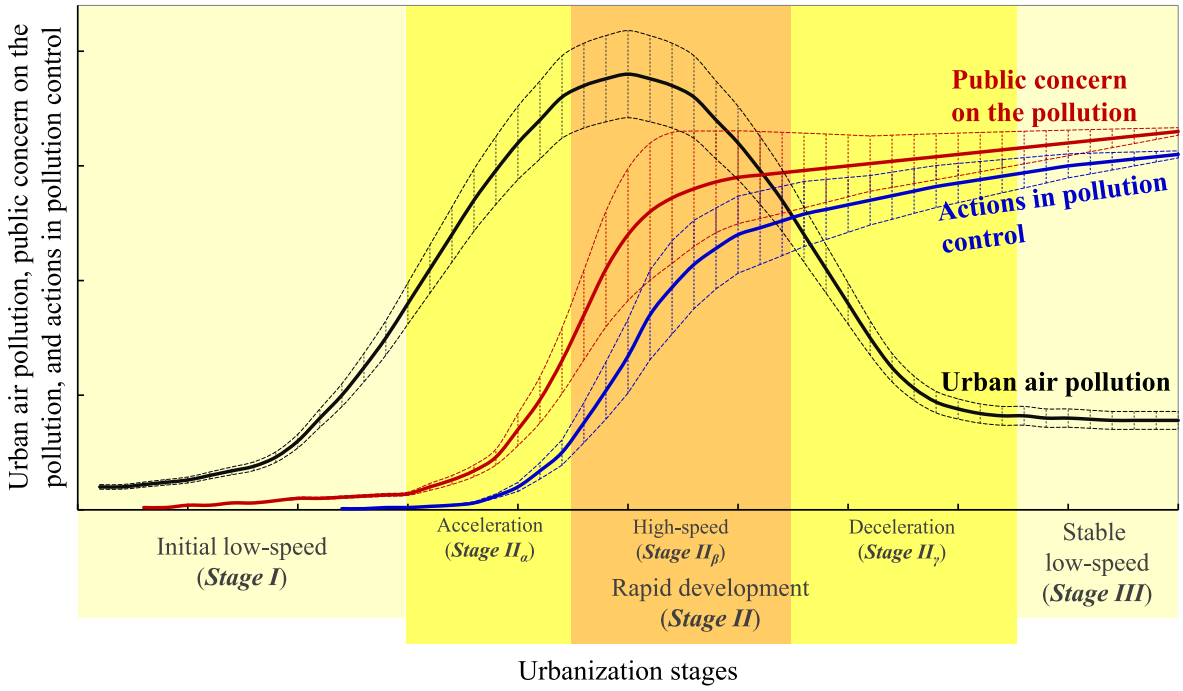

Fig. 4. Urban air pollution, public concern about air pollution, and actions or technologies in pollution control against urbanization stages.
Note: The black bold curve and the black dashed curves represent the urban air pollution against urbanization stages; the red bold curve and the red dashed curves represent the public concern on the urban air pollution against urbanization stages; the blue curve and the blue dashed curves represent the activities or technologies in air pollution control. The initial low-speed (Stage I) can be identified when the urbanization level is lower than 30%. Rapid development (Stage II) can be identified as an urbanization level from 30% to 70%, in which the stages of acceleration (Stage II_α), high-speed (Stage II_β) and deceleration (Stage II_γ) can be separated by urbanizations levels of 50%, and another is between 50% and 70%, which is depends on the country's development strategy.

enforcement of the law and regulations on air pollution control and prevention, as well as the lack of air quality monitoring and technological advancement, cities in South Africa are still facing air pollution (Hicks et al., 2001). Currently, South Africa is still struggling to find a better way to optimize the trade-off between air quality and urbanization under the needs of good material well-being and acceptable air quality.

2.11. India: unbalanced development with moderate air quality improvement

Low development levels and unreasonable economic structural development have resulted in increasingly heavy air pollution in India. In the 1980s, India commenced economic reform, which resulted in increasingly serious air pollution (Kohli, 2006). Although the Bhopal disaster alerted authorities to the need for air pollution prevention, the laws on air pollution are still not sufficient to ease pollution (Badami, 2005). In the early 1990s, information technology was well developed as a result of Indian talent; however, the imbalanced industrial structure in cities did not shift to an environmentally friendly approach. The low productivity manufacturing enterprises, unclean fossil fuel energy structure, inefficient transportation, and combustion of biofuels, especially cow dung, caused the further deterioration of urban and regional air quality (Sagar et al., 2016; Bonjour et al., 2013).

After the urbanization rate reached 30% in 2008, the air quality index was operationally released, the clean energy supplies improved, and a health-oriented strategy for air pollution was designed. However, air pollution is still a serious problem that limits the development of the country (Sagar et al., 2016). Both air pollution prevention policies and strategies were still need further construction with efficient practices (see the detail of policies and strategies for air quality management in India in Fig. 3), although the Air Pollution Control Plan was established in 2017. Since the urbanization rate still has a long way before reaching 50%, the prioritization of environmental protection in conjunction with urban and economic development is still difficult to manage.

3. The general process of urbanization, public concern about air pollution and activities in pollution control

To summarize the history of urbanization, in general, urbanization starts from the low-level stage, which is the initial low-speed stage (*Stage I*). It then moves to the high-level stage, which is the stable low-speed stage (*Stage III*), and transitions through a rapid development stage (Stage II) with the three sub-stages of acceleration (*Stage* II_α), high-speed (*Stage* II_β), and deceleration (*Stage* II_γ). During this long, complex and uncertain urbanization process, air pollution exhibits an inverse U-type pattern in which air pollution is stable with a slow increase during *stage I*, after which air pollution rapidly increases, reaches a peak, and decreases in *Stage II*. The air pollution stabilizes at a slightly worse level than that in *Stage I* during *Stage III*. While public concern and action on air pollution control show processes like logistic curves, the curve of actions on air pollution were later and lower than that of public concern about air pollution. Detailed descriptions of the three stages are provided in Fig. 4.

Stage I is the initial low-speed stage of urbanization that is characterized by low levels of and slight increases in air pollution and very limited understanding and public concern about the pollution. This characteristic was primarily due to the low level of productivity, slow urbanization, and small amount of natural resource consumption. Additionally, those activities are not concentrated in large cities in this stage but are dispersed to coincide with ecosystem productivity, which is the basic necessity of life. Moreover, the small amount of air pollutant emissions, which mostly come from biofuel combustion, are still within the self-purification ability of the natural ecosystem. In this stage, the regional and/or extreme atmospheric events are primarily caused by natural and/or climatic reasons (e.g., lighting causes forest fires; volcanic eruptions increase regional air pollution; and strong winds drive dust outbreaks). The scientific explanation of these natural events is still

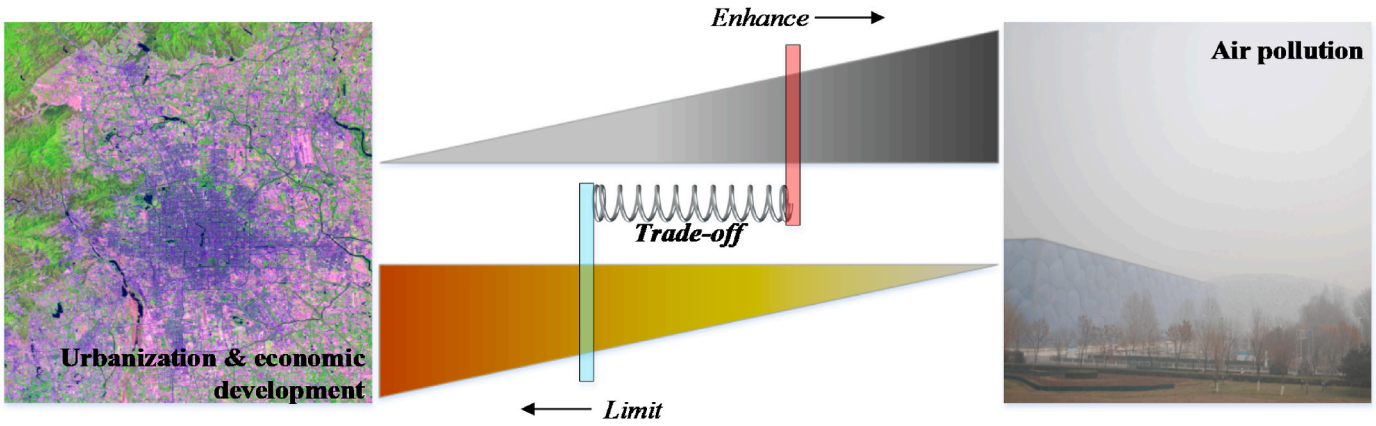

Fig. 5. A "wire spring"-like trade-off relationship between urban and economic development and air pollution. The light gray to dark gray triangle represents the air pollution level changes from light to heavy, and the red to yellow triangle represent the urbanization and economic development speed from high to low levels.

incomplete, unclear, and tends towards the "act of God" explanation. The understanding and public health concerns regarding air pollution are limited and irrational. This evidence could come from ancient to near-modern history, e.g., strong winds and heavy haze occulted the sky in the capital city of China's Yuan Dynasty (AD 1279–1368), while the emperor prayed for God to solve the problem (Han and Zhou, 2019). *Fumifugium* vehemently criticized air pollution with reasonable clues; however, the majority still believed that pollution fog was not harmful except that it made people unpleasant (Jenner, 1995).

After the long and slow urbanization process over several centuries, the world-shaking Industry Revolutions, global and regional economic collaboration and regulation (e.g., China's policy of reform and opening-up; the introduction and practice of free markets by the World Trade Organization (WTO)) brought urbanization into a rapid development stage (*Stage II*) with three sub-stages (*Stage* II_α; *Stage* II_β; *Stage* II_γ). In *Stage* II_α, the urban spatial pattern dramatically increases in a short period with increasingly intensive fossil fuel and natural resource consumption that results in significant air quality degeneration. Meanwhile, knowledge of pollution causes both authorities and the public to raise concerns. In this stage, the urban residents' material wealth improves rapidly; therefore, the air pollution caused by development will be ignored until extreme air pollution events occur. For example, long-term serious air pollution and serious public health damage incidents promote the rapid improvement of public awareness of air pollution, and thus force authorities to put air pollution control into action. In *Stage* II_β, urbanization remains rapid, while air pollution reaches its peak and starts decreasing. Urban authorities realize that the development methods in the previous stage resulted in severe air pollution that limited the sustainability of the cities. Action on pollutant emission control and ease pollution has thus received strong attention; however, those actions need time to take effect. The air pollution reaches a peak and starts to decrease, which is not easily recognized by the public, who has just experienced the most severe air pollution and remembers the pollution for a long time. Meanwhile, pollution control technology has become much more intensive than in the previous period due to massive public concern-induced technological innovation. After passing *Stage* II_β, urbanization goes into a deceleration period when air pollution significantly eases, while the understanding and recognition of air pollution becomes much deeper and more comprehensive than in the previous periods due to the public's awareness of the recent heavy pollution. Some attitude shifts can be highlighted: attention moves from short-term health impacts to long-term health impacts, from single contaminant air pollution to multi-contaminant air pollution (e.g., Han et al., 2018; Han et al., 2019). Although cities continue to consume a great amount of natural resources and fossil fuels accompanying air contamination reduction technology, increase in alternative clean energy usage, and off-site discharge of air contaminants reduce the total amount of air pollutant emissions in urban areas, considerably improving the air quality in regional scales.

After passing *Stage II*, urbanization enters a stable low-speed period (*Stage III*). The stable low-speed urbanization but the high urbanization level causes a slower increase in the large amounts of natural resources and energy consumption. Meanwhile, the compressive understanding of air pollution and the full life cycle of air pollutants are carefully examined and controlled. These factors make the air pollution in a very low level that is much better than that in *Stage II*; however, the air pollution level is still higher than that in Stage I, which was the natural unpolluted situation.

4. A way for future adaption of the trade-off between urbanization and air quality

The general process of urbanization, public concern about air pollution and activities in pollution control based on the understanding of typical countries' history provided both theoretical understanding and local practice solutions in supporting future adaption of the trade-off between urbanization and air quality. Thus, in this section, we summarized that a precautionary urbanization concept should be well understood by authorities, scientists and the public and that local practices with multi-stakeholder satisfaction should take action in urbanization processes. In Section 4.1, we emphasized that the environmental pollution precautionary urbanization concept should be implied. Detailed suggestions for authorities, scientific communities, and the public were provided. Then, the how to carry local practice was suggested in Section 4.2 in categories of education for new generations and adults to understand and satisfaction with both urban development and air quality. It further suggests that the scientific community provide detailed technological solutions for air pollution. Authorities could consider a better modern theory that engages in urbanization and air quality satisfaction.

4.1. The environmental pollution precautionary urbanization concept should be well understood among authorities, scientists and the public

Environmental pollution precautionary urbanization relates urban and economic development to air quality/pollution change considering their trade-off tension. The trade-off tension between the urbanization process and air pollution can be illustrated as having a "wire springs"-like function, as shown in Fig. 5. If air pollution imposes too large of a limit on the development of urbanization and the economy, the tension from the trade-off, or the wire springs, would become stronger; in the opposite situation, the tension would be weaker or more controllable and easier to solve.

The centuries-long history of the trade-off between urbanization and

air quality can be summarized as a typical "inverse-U" type curve, which is very similar to the environmental Kuznets curve (Fig. 4). In addition, until today, many or even most mid- and low-income countries are experiencing or will undergo the same process with varied temporal ranges again. By reviewing and taking advantage of the history of this trade-off, we argue that the precautionary principle should be strongly considered during the process of urbanization. Such a process would be critical in Stage II, as rapid urbanization is an urgent need for many low- and mid-income countries. However, under the current innovations in science and technology, the conventional "inverse-U″ can be greatly decreased. Moderate urbanization that is consistent with domestic technological improvement in air pollutant emission control would be a better strategy, and thus, air quality deterioration could be better handled. To carry out precautionary environmental protection during moderate urbanization, authorities, scientists and the public are suggested to work together and share their abilities, understanding, and advantages in realizing better practices. Details are included below.

It is recommended that authorities pay attention to the four following actions. First, the construction of a precautionary legal system for air quality management is one of the most important tools in all high-income countries for air pollution control and prevention; thus, the development of environmental laws should be given priority ahead of heavy pollution. Second, neither urban nor economic development should be strongly based on natural resources and energy consumption, but rather on environmentally friendly technological innovation should be encouraged to support urban and economic development. Third, development should follow the principles of clean resources and energy, low carbon emissions, and recyclable resources and energy. When designing national or regional long-term development strategies, precautionary consideration and priority should be given to environmental problems based on the prediction of the relationship between urban and economic development and air quality monitoring by remote sensing, meteorological indicators, modelling, and operational networks (e.g., van Donkelaar et al., 2010; Han et al., 2016; Han et al., 2018). Moreover, clean energy should be judged by life-cycle assessment rather than directly considering the terminal utilization forms (e.g., electronic vehicles are not environmentally friendly if the electricity comes from fossil fuel combustion). Last but not least, air quality management experience against urbanization and economic development is suggested from not only the high-income countries but also some mid- and low-income countries, e.g., China's ecological civilization concept for regulating development and ecological & environmental quality.

Scientific knowledge is recommended to combine the understanding from scientists and researchers of not only environmental chemistry and atmospheric physics and chemistry but also geography, economics, management, and ecology.

For instance, environmental chemistry analyses the main sources and formation of air pollutants from the chemical composition of the contaminants; geography analyses the relationship between geographical elements and urban air quality from the concept of human-land interactions; economics analyses the statistical correlation between different economic development models, inputs and outputs of economic factors, and air quality from the perspective of economic development; ecology analyses at a more macro scale through the complex urban and regional ecosystems formed by coupling social, economic, and natural factors with urban and regional air quality to provide eco-environmentally friendly strategies for urban development (Han, 2018). Thus, understanding the trade-off between urbanization and air quality could be diversified and integrated. Suggestions to policy-makers based on these scientific backgrounds could be well-directed, comprehensive, and practical.

Public understanding of air quality is suggested in both active and passive ways. The public perception of air quality is mainly passive. The daily breath-in of the air, reading news from multi-media, and people-to-people communication were the major ways in a general and specific understanding of air quality. Active strategies have been practised in some high-income countries through initiatives such as citizen science, which encourages the inclusion of citizens in air quality monitoring (e.g., Kaufman et al., 2017), who then share their understanding of air quality changes in neighbourhoods or through social media, which helps the public understand air quality through their personal experiences. Through active strategies, the public can successfully understand air quality by themselves. In the case of the remediation of heavy air pollution, the air quality cannot be instantly improved. However, it can be improved after a reasonable period, during which active methods could inform the public that the air quality is improving, thus reducing the pressure placed on the authorities by the public regarding air quality management.

4.2. Local practices for multi-stakeholder satisfaction would form urbanization and air quality

Local practices are some of the most important steps in air pollution prevention and control after the air pollution policies and laws enacted during rapid urbanization and economic development processes. Without efficient local systems, the air pollution and prevention bills would become simply paper documents with little practical value. In view of the long trade-off history, we argue that local practices with multi-stakeholder cooperation for multi-stakeholder satisfaction would form a better trade-off between urbanization and air quality. Such local practices should consider the following actions.

Environmental education is one of the best ways to allow new generations to understand better urbanization and environmental development concept. However, the current environmental education system still needs further careful construction. Environmental education should start with the review of certain environmental problems and then provide general ideas to beginners. Currently, most low- and mid-income countries do not have well-structured or comprehensive environmental education systems; examples can be found in high-income countries, such as the U.S., Japan and countries in Europe. Examples in similar cultural backgrounds and geographically close areas would be suitable but might not be the best choice to teach the young generation.

For common citizens, both active and passive education strategies are suggested. The passive strategy includes modern multi-media, e.g., Facebook, Twitter or other similar localized applications, which could spread and explain air pollution prevention and control acts and local practices well to a certain extent; however, without personal practices or close experiences, the understanding of common citizens is easy to ignore, as people have broad interests. The active methods are therefore useful to the average citizen. Such methods encourage and require residents to participate in certain air quality monitoring progress and air pollution control and prevention, allowing residents to understand the policies and the local implementation. Then, those understandings could be shared on social media or through people-to-people communication. Thus, common citizens could understand and participate in the local practices of air quality improvement and air pollution prevention and control through active and passive strategies.

For the scientific community, we suggest that historical and technological reviews from diverse perspectives and in numerous industrial sectors should be carried out to provide detailed technological solutions for air pollution. For the authorities, modern theories, e.g., the ecological civilization proposed and implemented in China (Xiao and Zhao, 2017), should be engaged in air quality improvement and air pollution control. However, such theories should guide local practice. For instance, both "timetables" and "roadmaps" for air pollution prevention and control are suggested, but a better combination of the two methods without limitations on urban and economic development should be well designed and practised with suitable concepts and theories.

5. Brief summary and conclusion

Urbanization is one of the significant transformations within recent

centuries, during which urbanization, along with industrialization and economic development, has caused profound impacts on human society and its living environment. In this article, we examined the history of air pollution under different stages of urbanization in typical high-, mid-, and low-income countries and, based on the review, summarized the general relationship between urbanization and air quality. Finally, we suggested future development of the trade-off between urbanization and air quality, especially for mid- and low-income countries that are undergoing or will undergo rapid urbanization and the predicted air pollution.

Based on the review, we highlighted the use of the precautionary principle for environmental pollution during urbanization development. Adequate attention and efficient local practices on air pollution control should be ahead of heavy pollution. Efficient local practices with multi-stakeholder satisfaction would form sustainable urbanization with favourable air quality. We hope this review will provide strong examples of the views and actions of countries on urbanization and air pollution in recent centuries, and thus serve as a reference for countries to design more appropriate actions towards better fulfilling the 11th goal of the UNSDG.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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