

Indoor Air Pollution and Its Control in China

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Abstract The status of indoor air pollution and its control in China are reviewed by introducing the pollution characteristics of major indoor air pollutants, the strategies and measures adopted to control indoor air pollution, as well as the major problems existing in the current indoor air pollution control. Although indoor pollution of formaldehyde and benzene has been effectively alleviated in recent years in China, indoor pollution of toluene and xylenes is still serious. Besides, studies show that indoor pollution of particulate matter (PM), biological pollutants, and semi-volatile organic compounds (SVOCs) might also be serious in China. The establishment and implementation of indoor air quality (IAQ)-related regulations and standards, the research on indoor air pollution and its control, and the development of indoor environmental monitoring and cleaning industry have played significant roles in preventing and controlling indoor air pollution in China. However, problems such as lack of mandatory standards for IAQ, lack of regulation and labeling of pollutant emissions from indoor decorating and refurbishing materials, lack of an effective performance evaluation system for air cleaning products, and lack of proper maintenance of air cleaners remain to be solved for further improvement of IAQ.

Keywords Characteristics, China, Countermeasures, Indoor air pollution

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1 Introduction

Indoor air quality (IAQ) problems have always existed in China due to the extensive use of solid fuels (coal and biomass) in simple stoves for household heating and cooking (in the vast rural and also many urban areas) as well as some traditional but unhealthy living habits, such as cooking using stir frying and deep frying methods, smoking in homes, using commodes with no flushing systems (in most rural areas), and living together with livestock (in some rural areas). According to studies of relationship between IAQ and human health conducted in the 1980s, the main indoor air pollutants at that time were fuel combustion products, cooking fumes, and environmental tobacco smoke (ETS); poor IAQ was associated with a variety of negative health outcomes, the most notable being lung cancer [1–5].

In order to alleviate indoor air pollution from household energy use and unhealthy lifestyle, many interventions have been introduced in China, including technological interventions (e.g., stove and ventilation improvement, development and use of clean energy), behavior interventions (e.g., cooking methods change, indoor smoking avoidance), health education, and social mobilization [4–6]. The China National Improved Stove Program (CNISP), which resulted in the installation of 129 million new stoves in rural homes (representing around 65% of all rural households) between 1982 and 1992, has proved to greatly improve the IAQ in rural China [4, 5, 7].

Since the late 1990s, more and more residents in China have started to own apartments or townhouses with the deepening of city and township housing reform,

and as personal incomes have rapidly increased with the high-speed economic growth, indoor decoration and refurbishment of newly constructed or existing apartments have become very popular, which has brought not only great prosperity to the indoor decoration and refurbishment industry but also extremely serious IAQ problems to the country. On the one hand, due to the lack and the lax enforcement of regulations and standards for indoor decorating and refurbishing materials, some materials and products containing large amounts of harmful substances have entered the market and then the indoor environments, releasing various pollutants such as formaldehyde and volatile organic compounds (VOCs) during and after the decoration and refurbishment. On the other hand, air-conditioning systems have been installed in almost all modern buildings with the improvement of living standards. In order to save energy during the use of air-conditioning, most buildings have been constructed to be tightly sealed, leading to a significantly reduced indoor-outdoor air exchange. As a result, pollutants released from inferior decorating and refurbishing materials build up in indoor air, severely deteriorating the IAQ and thus posing serious hazards to human health. In June 2001, the Beijing Changping District People's Court judged China's first damages lawsuit for indoor air pollution. Formaldehyde, in a concentration of 1.56 mg/m^3 (surpassing the indicated standard by 19.5 times) in the owner's bedroom, resulted in the lawsuit.

Excessive complaints relevant to indoor air pollution caused by interior decoration and refurbishment and the prevalence of sick building syndrome (SBS) have aroused deep concern of IAQ problems from the government and the public. From June to September 2001, Vice-Premiers Wen Jiabao and Li Lanqing made important instructions on interior decoration pollution three times in succession, calling for great attention to the pollution and requesting relevant departments to develop effective pollution control measures. In order to increase public awareness of the importance of IAQ, propaganda and education of indoor environmental knowledge, especially the causes and effects of indoor air pollution, have been greatly strengthened.

The government's guidance and the increasing public requirements for improving IAQ have significantly promoted the establishment of IAQ-related regulations and standards, the research on indoor air pollution and its control, and the development of indoor environmental monitoring and cleaning industry in China, which provide solid foundations for prevention and control of indoor air pollution. However, the existing pollution control measures mostly focus on the pollutants originating from indoor decorating and refurbishing materials (mainly formaldehyde and VOCs). Other indoor air pollutants such as particulate matter (PM), biological pollutants, and semi-volatile organic compounds (SVOCs) have not obtained adequate attention in China.

In this chapter, the current status and future trends of indoor air pollution in China are introduced first. Then the strategies and measures adopted to control indoor air pollution are reviewed. Finally, major problems existing in the current indoor air pollution control are analyzed.

2 Current Status and Future Trends of Indoor Air Pollution in China

In order to get an insight into the current status and future trends of indoor air pollution in China, pollution characteristics of major indoor air pollutants, including formaldehyde, VOCs, PM, biological pollutants, and SVOCs, are introduced as follows.

2.1 Formaldehyde

Formaldehyde is the most common and the best-known indoor air pollutant. In homes, the most significant sources of formaldehyde are likely to be engineered wood products made by using adhesives that contain urea-formaldehyde (UF) resins. Engineered wood products made for indoor use include particleboard (used as subflooring and shelving and in cabinetry and furniture), hardwood plywood paneling (used for decorative wall coverings and used in cabinets and furniture), and medium-density fiberboard (used for drawer fronts, cabinets, and furniture tops).

Indoor formaldehyde pollution was very serious in the early 2000s in China due to the extensive use of engineered wood products with high formaldehyde emission in home decoration and refurbishment. A survey conducted in 2003 in six cities of China indicated that the percentage of recently renovated homes with indoor formaldehyde concentrations above the national standard (0.10 mg/m^3) reached 82.3% (Table 1) [8].

In recent years, formaldehyde pollution has been effectively alleviated by forbidding the use of substandard engineered wood products in indoor decoration and refurbishment via implementing the mandatory national standard, GB 18580-2001 “Indoor decorating and refurbishing materials – Limit of formaldehyde emission of wood-based panels and finishing products.” Table 2 shows the passing rates of formaldehyde emission of medium-density fiberboard and blockboard on the market in different years [9]. It can be seen that for both kinds of wood-based panels, the passing rates of formaldehyde emission in 2009–2011 were much higher than those in 2003 or 2004.

As the awareness of the importance of IAQ has been increasing in these years, public demand for healthy/green/nontoxic decorating and refurbishing materials is growing. Predictably, the indoor formaldehyde pollution will be further reduced or completely eliminated with the development of wood-based panels with lower or zero formaldehyde emission in the near future.

2.2 Volatile Organic Compounds

VOCs have become major indoor air pollutants in China since the prevalence of interior decoration and refurbishment. Indoor sources of VOCs mainly include

Table 1 Indoor formaldehyde concentrations in recently renovated homes in six cities of China^a [8]

City	Sample number	Formaldehyde concentration (mg/m ³)		Percentage above standard ^b (%)
		Mean ± SD	Range	
Beijing	530	0.210 ± 0.152	0.025–1.382	75.5
Tianjin	164	0.267 ± 0.170	0.025–1.100	89.6
Shanghai	182	0.205 ± 0.135	0.025–0.869	79.1
Chongqi	198	0.142 ± 0.084	0.025–0.461	64.6
Shizuishan	212	0.610 ± 0.311	0.104–1.712	100
Changchun	201	0.412 ± 0.208	0.025–1.243	96.0
Total	1,487	0.290 ± 0.238	0.025–1.712	82.3

^aSampling time: January to April 2003; time since renovation: <6 months

^bThe “Indoor air quality standard” of China (GB/T 18883-2002) stipulates the indoor limit of 0.10 mg/m³ (1-h average) for formaldehyde

Table 2 Passing rates of formaldehyde emission of medium-density fiberboard and blockboard^a

Year	Medium-density fiberboard		Blockboard	
	Sample number	Passing rate (%)	Sample number	Passing rate (%)
2003	41	75.6	–	–
2004	–	–	91	80.2
2009	93	86.0	188	89.4
2010	119	93.3	1,206	90.8
2011	189	96.3	200	88.0

^aCalculated from inspection results by the General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China [9]

solvent coatings for woodenware, interior architectural coatings, adhesives, wood-based furniture, carpets, and carpet cushions. Generally, various kinds of VOCs coexist in indoor environments, in concentrations decreasing with time after renovation.

Similar to formaldehyde, indoor pollution of VOCs was also very serious in the early 2000s in China. An investigation conducted from 2002 to 2004 on VOCs concentrations in 1,241 recently renovated residences in China showed that the average concentration of total volatile organic compounds (TVOC) was as high as 2.18 mg/m³ and benzene, toluene, and xylenes (BTX) were the primary VOCs pollutants in indoor air, with average concentrations of 124.04, 258.90, and 189.68 µg/m³, respectively (Table 3) [10].

The high concentrations of BTX in newly renovated buildings could be mainly attributed to the widespread use of BTX as solvents and diluents for coatings and adhesives used in interior decoration and refurbishment. Considering the high toxicity of benzene to human beings, the use of benzene has been forbidden since 2002 by implementing mandatory national standards, including GB 50325-2001 “Code for indoor environmental pollution control of civil building engineering,” GB 18581-2001 “Indoor decorating and refurbishing materials – Limit of harmful substances of solvent coatings for woodenware,” and GB 18583-2001 “Indoor

Table 3 Indoor concentrations of benzene, toluene, xylenes, and TVOC in recently renovated residences in China^a [10]

Pollutant	Sample number	Concentration (BTX: $\mu\text{g}/\text{m}^3$; TVOC: mg/m^3)	
		Mean \pm SD	Range
Benzene	843	124.04 \pm 272.60	0.18–4,284.20
Toluene	901	258.90 \pm 671.98	0.04–9,093.70
Xylenes	958	189.68 \pm 561.16	0.05–10,413.70
TVOC	982	2.18 \pm 12.94	0.005–394.44

^aSampling area: Beijing, Tianjin, Shanghai, Dalian, Shizuishan, Pingliang, Zhuhai, Changchun, and Chongqing; sampling time: May 2002 to November 2004; time since renovation: <12 months

Table 4 Indoor concentrations of benzene, toluene, and xylenes in a newly renovated hotel in Beijing^a [11]

Pollutant	Sampling site	Sampling times	Concentration ($\mu\text{g}/\text{m}^3$)		Indoor limit ^b ($\mu\text{g}/\text{m}^3$)
			Mean	Range	
Benzene	Guest room	6	107.0	45.7–178.8	110 (1-h average)
	Conference room	6	87.0	21.7–191.5	
Toluene	Guest room	6	400.7	159.0–639.7	200 (1-h average)
	Conference room	6	174.3	47.1–330.8	
Xylenes	Guest room	6	1,623.4	1,185.7–2,484.9	200 (1-h average)
	Conference room	6	402.4	42.1–1,037.0	

^aSampling time: April to June 2010

^bStipulated by GB/T 18883-2002 “Indoor air quality standard”

decorating and refurbishing materials – Limit of harmful substances of adhesives.” Meanwhile, the use of toluene and xylenes has been limited although they are less toxic compared to benzene. Field survey data prove that implementation of these standards has indeed reduced indoor pollution of benzene; however, indoor pollution of toluene and xylenes is still serious (Table 4) [11]. In order to further control the pollution of toluene and xylenes, the abovementioned national standards have been revised successively in recent years to strengthen the limits of toluene and xylenes.

Besides promoting the use of less toxic organic solvents, great efforts have also been made in China to develop coatings and adhesives with no organic solvents, such as water-based coatings and adhesives, powder coatings, radiation curable coatings, and hot melt adhesives. Increasing use of these environment-friendly products in interior decoration and refurbishment would greatly reduce the indoor pollution of VOCs.

2.3 Particulate Matter

Compared with gaseous pollutants (formaldehyde, VOCs), indoor particulate matter (PM) has gathered much less concern in China, although inhalable PM

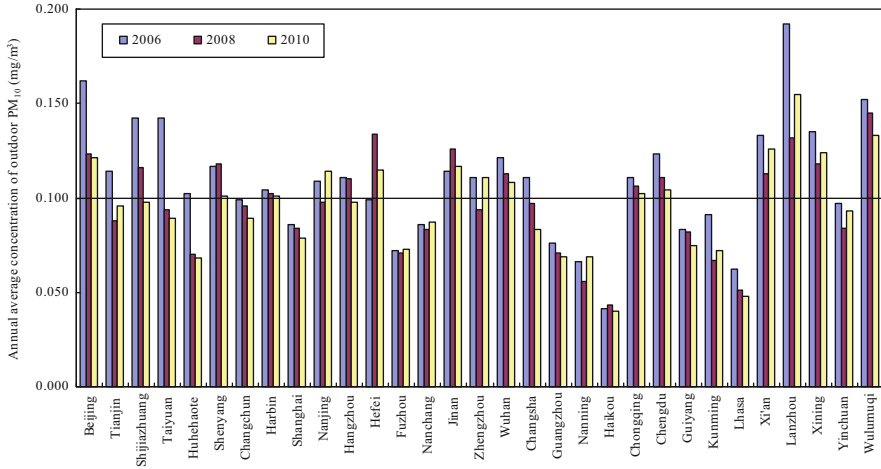


Fig. 1 Annual average concentrations of outdoor PM₁₀ in 31 cities in China [14–16]

(PM₁₀, particles smaller than or equal to 10 μm in aerodynamic diameter) is included in the “Indoor air quality standard” (GB/T 18883-2002) as one of the 13 controlled chemical pollutants.

In China, indoor PM mainly originates from outdoor sources such as fuel burning (mainly coal), vehicle emissions, and transformation of gaseous emissions in the atmosphere [12]. According to the air quality monitoring results of major cities in China since 2000, PM₁₀ has been the most important primary pollutant (among PM₁₀, SO₂, NO₂, CO, and O₃) in ambient air [13]. Figure 1 illustrates the annual average concentrations of PM₁₀ in 31 cities in China for the years 2006, 2008, and 2010 [14–16]. It can be seen that the overall PM₁₀ pollution was still serious in 2010 although an alleviation trend was observed for most cities. In 2006, 2008, and 2010, 19, 14, and 14 monitored cities had annual average concentrations of outdoor PM₁₀ exceeding the limit value (0.10 mg/m³, annual average) stipulated by GB 3095-1996 “Ambient air quality standard” (Fig. 1).

On the other hand, the frequent occurrence of haze in many cities (especially mega cities such as Beijing, Shanghai, and Guangzhou) of China since the autumn of 2011 indicates that the concentration of fine particles (PM_{2.5}, particles smaller than or equal to 2.5 μm in aerodynamic diameter) in ambient air has been increasing in recent years although the PM₁₀ concentration tends to decrease. It is well known that fine particles are more hazardous to human health than coarse particles since they can travel deep into the lungs, enter the bloodstream, and penetrate into cells. In the newly revised “Ambient air quality standard” (GB 3095-2012), PM_{2.5} has been included as another common pollutant besides PM₁₀, SO₂, NO₂, CO, and O₃.

Since outdoor PM can migrate into indoor environments through fissures and cracks in the building structures, high concentration of PM in ambient air can not only deteriorate the quality of outdoor air but also negatively influence the quality of indoor air. Shi et al. [17] investigated the concentrations of PM in indoor and

Table 5 Concentrations of PM₁₀ and PM_{2.5} in indoor and outdoor air of residences in Taiyuan [17]

Sampling time	Sampling site	Sample number	Average concentration (mg/m ³)	
			PM ₁₀	PM _{2.5}
Heating period	Indoor	438	0.327	0.107
	Outdoor	319	0.547	0.123
Non-heating period	Indoor	485	0.239	0.089
	Outdoor	457	0.321	0.109

Table 6 Concentrations of PM₁₀ in indoor (I) and outdoor (O) air of residences and the I/O ratios [18]

Residence	Sampling times	Average concentration of PM ₁₀ (mg/m ³)		
		Indoor	Outdoor	I/O ratio
Without indoor PM source	3	0.093	0.107	0.869
With smoking	3	0.109	0.060	1.817
With cooking	3	0.067	0.060	1.117

outdoor air of 541 homes in Taiyuan (the capital of Shanxi province) during both heating and non-heating periods of 2004–2006. Results showed that the PM concentration in outdoor air was always higher than that in indoor air and both the indoor and outdoor concentrations of PM during the heating period were higher than those during the non-heating period (Table 5). Correlation analysis proved that the outdoor PM pollution contributed greatly to the indoor PM pollution, especially during the heating period.

In addition to outdoor sources, indoor PM can also originate from indoor sources such as fuel-burning, cooking, smoking, and sweeping activities. For modern buildings with low ventilation rates, the presence of indoor sources may result in higher PM concentrations in indoor environments than in outdoor air (Table 6) [18].

In view of the severe outdoor pollution of PM, the significant influence of outdoor pollution on indoor environments as well as the serious health risks from PM exposure, strengthening research on indoor PM pollution and its control, has become imperative in China.

2.4 Biological Pollutants

Biological pollutants in indoor environments mainly include bacteria (including endotoxins from bacteria), fungi (including spores and cell fragments of fungi), viruses, dust mites, and animal dandruff. These pollutants exist in the air mainly as bioaerosols (biological particles). Major indoor sources of biological pollutants at residential homes include human occupants, pets, house dust, organic waste, as well as the heating, ventilation, and air-conditioning (HVAC) system [19–23]. Adverse health effects/diseases related to biological pollutants exposure can be divided into

two categories: infectious diseases such as influenza, viral pneumonia (e.g., severe acute respiratory syndrome, SARS) and bacterial pneumonia (e.g., Legionnaires' disease) and allergic diseases such as allergic asthma, allergic rhinitis, and allergic alveolitis [24].

Although studies on concentrations and health effects of indoor biological pollutants started in the 1950s in China [25–31], control of indoor biological pollution had not obtained adequate attention until the outbreak of SARS in 2003. Since bad-designed ventilation systems were considered to have played important roles in the rapid and widespread dissemination of the SARS virus, air-conditioning and ventilation systems have become the focus of concern in the control of indoor biological pollution.

In 2004, a national inspection on central air-conditioning and ventilation systems in 937 public places, including hotels, restaurants, shopping malls, and supermarkets, was performed by the Ministry of Health of the People's Republic of China. The report showed that around half of the samples were heavily polluted with high concentrations of dust, bacteria, and fungi and the passing rate was only 6%. The maximum concentrations of dust, bacteria, and fungi on the inner surface of air ducts reached 486 g/m^2 , $277 \times 10^4 \text{ cfu/(g dust)}$, and $480 \times 10^4 \text{ cfu/(g dust)}$, respectively [32]. During the use of air-conditioning, the dust containing bacteria and fungi can be transferred into indoor environments by the airstream, causing serious biological pollution and then adverse health effects.

In order to prevent and control the pollution caused by air-conditioning and ventilation systems, the Ministry of Health of the People's Republic of China issued a comprehensive hygiene management approach and three supporting hygienic norms (hygienic norm, hygienic assessment norm, and cleaning norm) for central air-conditioning and ventilation systems in public places, which came into effect on March 1, 2006. Tables 7 and 8 present some survey data on hygienic conditions of central air-conditioning and ventilation systems in public places of China after implementing the management approach and hygienic norms [33–45]. It can be seen that the overall concentration-passing rates of typical pollutants both on the inner surface of air ducts (Table 7) and in the supply air (Table 8) have been significantly improved in recent years, indicating an effective control of biological pollution related with central air-conditioning and ventilation systems.

Compared with public places, however, much less concern has been given to control of biological pollution in residences, which should also be addressed in the future to protect residents from hazards of ubiquitous biological pollutants.

2.5 *Semi-volatile Organic Compounds*

SVOCs are organic compounds with boiling points in the range of 240–400°C [46]. They are considered as new-type chemical pollutants in indoor air and have become a hot research topic in the field of indoor environment and health in recent years. Major sources of indoor SVOCs include materials and products containing

Table 7 Concentration-passing rates of dust, bacteria, and fungi on inner surface of air ducts of central air-conditioning and ventilation systems in public places of China^a

Area	Sampling time	Number of public place	Dust			Bacteria			Fungi			References
			Sample number	Passing rate ^b (%)	Sample number	Passing rate ^c (%)	Sample number	Passing rate ^d (%)				
Hebei (Shijiazhuang)	2010	22	110	70.0	110	88.2	110	80.0	[33]			
Hunan	2010	24	24	58.3	24	75.0	24	100.0	[34]			
Pearl River Delta	2009–2010	25	170	68.2	170	99.4	170	100.0	[35]			
Guangdong (Zhongshan)	2009	18	183	95.6	183	94.5	183	88.0	[36]			
Fujian (Xiamen)	2009	43	398	98.5	398	97.2	398	95.0	[37]			
Zhejiang	2009	240	237	75.5	236	94.9	236	70.8	[38]			
Jiangsu	2009	97	312	67.3	458	90.6	456	89.7	[39]			
Liaoning (Dalian)	2008	14	14	64.3	69	97.1	69	97.1	[40]			
Beijing	2008	12	56	67.9	56	76.8	56	53.6	[41]			
Hunan (Changsha)	2008	15	61	50.8	61	50.8	61	59.0	[41]			
Tianjin	2006	16	–	–	113	89.4	113	71.7	[42]			
Henan (Jiaozuo)	2006	16	96	59.4	96	47.9	96	41.7	[43]			

^aEvaluated based on the “Hygienic norm for central air-conditioning and ventilation systems in public places” of China

^bPercentage of samples with dust concentrations $\leq 20 \text{ g/m}^3$

^cPercentage of samples with bacteria concentrations $\leq 100 \text{ cfu/cm}^2$

^dPercentage of samples with fungi concentrations $\leq 100 \text{ cfu/cm}^2$

Table 8 Concentration-passing rates of PM₁₀, bacteria, fungi, and β-hemolytic streptococcus in supply air of central air-conditioning and ventilation systems in public places of China^a

Area	Sampling time	Number of public place	PM ₁₀			Bacteria			Fungi			β-Hemolytic streptococcus			References
			Sample number	Passing rate ^b (%)	Sample number	Passing rate ^c (%)	Sample number	Passing rate ^d (%)	Sample number	Passing rate ^e (%)	Sample number	Passing rate ^e (%)			
Zhejiang	2011	180	179	79.3	179	62.6	179	74.3	179	100.0	179	100.0	[44]		
Hebei (Shijiazhuang)	2010	22	-	-	110	95.4	110	99.1	110	100.0	110	100.0	[33]		
Pearl River Delta	2009–2010	25	112	75.9	112	73.2	112	97.3	112	100.0	112	100.0	[35]		
Guangdong (Zhongshan)	2009	18	-	-	183	86.3	183	76.5	183	100.0	183	100.0	[36]		
Fujian (Xiamen)	2009	43	31	93.6	31	90.3	31	96.8	31	100.0	31	100.0	[37]		
Zhejiang	2009	240	239	64.4	240	71.7	240	76.7	240	100.0	240	100.0	[38]		
Liaoning (Dalian)	2008	14	14	57.1	66	47.0	66	71.2	66	-	-	-	[40]		
Beijing	2008	12	56	33.9	56	58.9	56	100.0	56	-	-	-	[41]		
Hunan (Changsha)	2008	15	33	27.3	33	39.4	33	48.5	33	-	-	-	[41]		
Tianjin	2006	16	-	-	164	40.2	164	59.1	164	100.0	164	100.0	[42]		
Heilongjiang (Harbin)	2006	20	20	45.0	20	0	20	75.0	20	-	-	-	[45]		

^aEvaluated based on the "Hygienic norm for central air-conditioning and ventilation systems in public places" of China

^bPercentage of samples with PM₁₀ concentrations ≤ 0.08 mg/m³

^cPercentage of samples with bacteria concentrations ≤ 500 cfu/cm³

^dPercentage of samples with fungi concentrations ≤ 500 cfu/cm³

^ePercentage of samples with no detectable β-hemolytic streptococcus

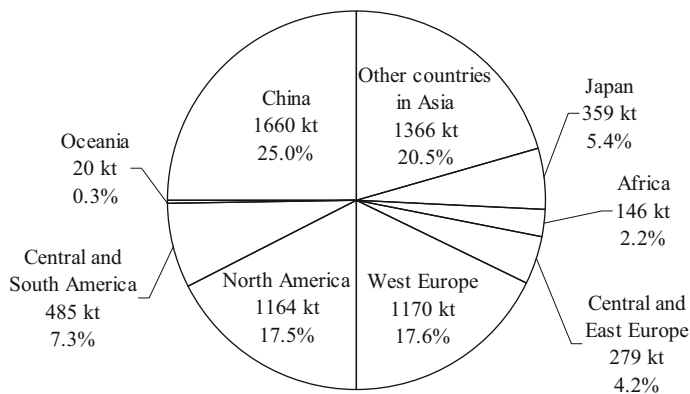


Fig. 2 Consumption of plasticizers in the world in 2006 by region [47, 48]

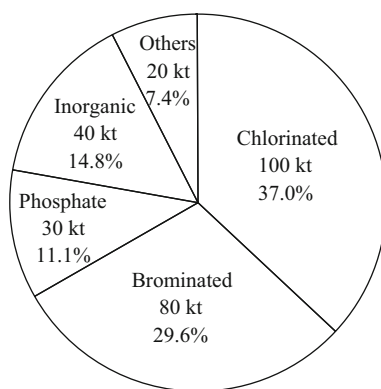


Fig. 3 Production of flame retardants in China in 2006 by type [47]

plasticizers (additives in plastics to enhance their flexibility and extensibility) and flame retardants (additives in materials to reduce their combustibility), household pesticides, and human activities such as smoking, incense burning, and cooking [47].

China produces and consumes the largest amounts of plasticizers in the world. As shown in Fig. 2, 25% of plasticizers in the world were consumed by China in 2006 [47, 48]. Phthalates are produced and consumed in the largest amounts among all plasticizers, with diethylhexyl phthalate (DEHP) and dibutyl phthalate (DBP) being the two main types [47, 48].

The production and consumption of flame retardants are also very high in China. In 2006, China produced 270-kt flame retardants, 66.6% of which were halogen-based (chlorinated and brominated) (Fig. 3) [47]. The largest production and consumption among halogen-based flame retardants belong to decabromodiphenyl ether (DecaBDE) due to its lowest price and highest performance [47].

China also produces and consumes great amounts of pesticides, the main active ingredients of which are SVOCs [47]. Besides, field measurements show that smoking, coal combustion, and Chinese cooking produce large quantities of polycyclic aromatic hydrocarbons (PAHs) [49–51].

Epidemiological and toxicological studies have proved that SVOCs exposure can cause serious harm to human health, including harming the endocrine and reproductive systems [52–55]. In recent years in China, indoor SVOCs pollution has gathered escalating concern from the researchers. Several studies on pollution and exposure levels of indoor SVOCs have been conducted, and the results show that indoor SVOCs pollution might be very serious in China [56–60]. In order to prevent and control this new type of pollution, more concern from the government as well as the public is required and more systematic and in-depth research should be carried out.

3 Strategies and Measures for Control of Indoor Air Pollution

In order to control indoor air pollution, a series of strategies and measures have been adopted in China since the 1980s, including enacting regulations and standards, strengthening research on indoor air pollution and its control, and developing indoor environmental monitoring and cleaning industry.

3.1 Formulating and Improving Regulations and Standards

Legislation concerning IAQ in China started in the late 1980s based on broad surveys and studies on health effects of indoor environments. In 1988, the Ministry of Health of the People's Republic of China issued a set of hygienic standards for public places, in which concentration limits of carbon monoxide (CO), carbon dioxide (CO₂), inhalable particulate matter (PM₁₀), and bacteria were stipulated. These standards played important roles in improving sanitation in public places as well as controlling the propagation of diseases. Revised versions of these standards, GB 9663–9673-1996 and GB 16153-1996, were promulgated by the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China in 1996. In the revised standards, the concentration limits of formaldehyde were also included.

The first hygienic standard for residences, GB/T 16127-1995 “Hygienic standard for formaldehyde in indoor air of house,” was issued by the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China in 1995. After that, a series of hygienic standards for other pollutants in indoor air were successively promulgated by the General Administration of Quality Supervision, Inspection and Quarantine and/or the Ministry of Health of the

People's Republic of China, including GB/T 17093-1997 (bacteria total), GB/T 17094-1997 (carbon dioxide), GB/T 17095-1997 (inhalable particulate matter), GB/T 17096-1997 (nitrogen oxides), GB/T 17097-1997 (sulfur dioxide), WS/T 182-1999 (benzo(a)pyrene (B(a)P)), GB/T 18202-2000 (ozone), GB/T 18203-2000 (*Streptococcus hemolyticus*), and GB 18468-2001 (*p*-dichlorobenzene). These standards laid good foundations for the establishment of IAQ standard in China.

The prevalence of indoor decoration and refurbishment of existing and new buildings since the late 1990s has caused serious indoor air pollution in China due to the extensive use of indoor decorating and refurbishing materials containing large amounts of harmful substances. In order to control indoor air pollution effectively, the Chinese government has greatly accelerated the pace of establishing IAQ-related regulations and standards since 2000.

GB 50325-2001 "Code for indoor environmental pollution control of civil building engineering," jointly issued by the Ministry of Construction and the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China on November 26, 2001, took effect on January 1, 2002. This code is applicable for the newly constructed, extended, or renovated civil building engineering, which is divided into two groups: Group I includes residential house, hospital, home for the elderly, kindergarten, and classroom and Group II includes office building, shopping center, hotel, public place of entertainment, bookstore, library, exhibition, gymnasium, waiting room of public transit means, dining room, and barbershop. The code prescribes the requirements for building and decorating materials (inorganic nonmetallic main materials for buildings and decorating materials such as wood-based panels, coatings, adhesives, and water-based treatment agents), survey and design (site investigation on soil radon concentration and material selection), construction, inspection, and acceptance to control the concentrations of radon, formaldehyde, benzene, ammonia, and TVOC in civil buildings.

GB 50325-2001 played important roles in preventing and controlling the indoor air pollution caused by building and decorating materials. Considering the development of construction, decoration, and refurbishment industry as well as the changes in characteristics of indoor air pollution in China, the code was revised first in 2006 and then in 2010. GB 50325-2010, which was brought into effect on June 1, 2011, strengthens the original requirements for pollution control and includes new requirements as well. For instance, for solvent-based coatings used in civil building engineering, the content limits of TVOC and benzene have been strengthened, and a limit value for the total content of toluene, xylenes, and ethylbenzene has been added in GB 50325-2010 (Table 9) [61, 62]. GB 50325-2010 also strengthens the concentration limits of formaldehyde and ammonia for Group II civil building engineering (Table 10) [61, 62].

In order to improve the quality and regulate the production of indoor decorating and refurbishing materials in China, the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China issued ten mandatory national standards for limits of harmful substances in indoor decorating and refurbishing materials on December 10, 2001, which came into effect on

Table 9 Limits of harmful substances in solvent-based coatings used in civil building engineering [61, 62]

	TVOC (g/L)		Benzene (%)		Toluene + xylenes + ethylbenzene (%)	
	GB 50325-2001	GB 50325-2010	GB 50325-2001	GB 50325-2010	GB 50325-2001	GB 50325-2010
Solvent-based coatings						
Alkyd coatings	≤550	≤500	≤0.5	≤0.3	–	≤5
Nitrocellulose coatings	≤750	≤720	≤0.5	≤0.3	–	≤30
Polyurethane coatings	≤700	≤670	≤0.5	≤0.3	–	≤30
Phenolic antirust coatings	≤270	≤270	≤0.5	≤0.3	–	–

Table 10 Limits of environmental pollutants in civil building engineering [61, 62]

Pollutant	Group I civil building engineering		Group II civil building engineering	
	GB 50325-2001	GB 50325-2010	GB 50325-2001	GB 50325-2010
Radon (Bq/m ³)	≤200	≤200	≤400	≤400
Formaldehyde (mg/m ³)	≤0.08	≤0.08	≤0.12	≤0.10
Benzene (mg/m ³)	≤0.09	≤0.09	≤0.09	≤0.09
Ammonia (mg/m ³)	≤0.2	≤0.2	≤0.5	≤0.2
TVOC (mg/m ³)	≤0.5	≤0.5	≤0.6	≤0.6

January 1, 2002 (Table 11). These standards provide mighty technical and legal support for ultimately improving IAQ and safeguarding people's health by explicitly limiting the contents and emission intensity of harmful chemicals of indoor decorating and refurbishing materials. Materials and products that fail to meet the standards were forbidden to enter the market from July 1, 2002. Inspections of the product quality have been conducted frequently, and punishment for production, sale, and use of substandard products has been enforced to ensure the quality of construction, decoration, and refurbishment. Consumers can take the mandatory national standards as authoritative references when they address any dispute arising from indoor decoration and refurbishment. Some specifications in these standards, such as those for VOCs in interior architectural coatings, conform to those standards in the European Union and the USA.

In recent years, the Standardization Administration of the People's Republic of China has been revising these standards by strengthening some of the limits as well as including more limited harmful substances and materials taking into account the increasing requirements for better IAQ and the development of indoor decoration and refurbishment industry (Table 11).

The first national indoor air quality standard (GB/T 18883-2002), released jointly by the General Administration of Quality Supervision, Inspection and Quarantine, the Ministry of Health, and the Ministry of Environmental Protection of the People's Republic of China, came into effect on March 1, 2003. The standard

Table 11 Standards for indoor decorating and refurbishing materials

Standard number	Standard name	Revised version (implementation date)
GB 18580-2001	Indoor decorating and refurbishing materials – Limit of formaldehyde emission of wood-based panels and finishing products	–
GB 18581-2001	Indoor decorating and refurbishing materials – Limit of harmful substances of solvent coatings for woodenware	GB 18581-2009 (June 1, 2010)
GB 18582-2001	Indoor decorating and refurbishing materials – Limit of harmful substances of interior architectural coatings	GB 18582-2008 (October 1, 2008)
GB 18583-2001	Indoor decorating and refurbishing materials – Limit of harmful substances of adhesives	GB 18583-2008 (September 1, 2009)
GB 18584-2001	Indoor decorating and refurbishing materials – Limit of harmful substances of wood-based furniture	–
GB 18585-2001	Indoor decorating and refurbishing materials – Limit of harmful substances of wallpapers	–
GB 18586-2001	Indoor decorating and refurbishing materials – Limit of harmful substances of poly(vinyl chloride) floor coverings	–
GB 18587-2001	Indoor decorating and refurbishing materials – Limit of harmful substances emitted from carpets, carpet cushions and adhesives	–
GB 18588-2001	Limit of ammonia emitted from concrete admixtures	–
GB 6566-2001	Limit of radionuclides in building materials	GB 6566-2010 (July 1, 2011)

stipulates the requirements for IAQ parameters, including physical, chemical, biological, and radioactive parameters relevant to human health (Table 12) [63], and the relevant testing methods. Besides the measurable indices, the feeling index of “no odor in indoor air” is also included in this standard. The standard is suitable for residential and office buildings. The built environments of other buildings can be designed or evaluated according to it as well. GB/T 18883-2002 provides a scientific basis for IAQ evaluation and has played important roles in preventing and controlling indoor air pollution and safeguarding people’s health in China.

Air-conditioning and ventilation systems can be important sources of indoor pollutants and major propagation pathway of airborne diseases. In order to strengthen the management of central air-conditioning and ventilation systems in public places to protect the public health, the Ministry of Health of the People’s Republic of China promulgated “Hygiene management approach of central air-conditioning and ventilation systems in public places” and three supporting hygienic norms in 2006.

The “Hygienic norm for central air-conditioning and ventilation systems in public places” prescribes the requirements and testing methods of hygienic conditions of central air-conditioning and ventilation systems in public places. The hygienic requirements for air supply and inner surface of air ducts are listed in

Table 12 Indoor air quality standard (GB/T 18883-2002) [63]

Parameter category	Parameter	Unit	Standard value	Note
Physical	Temperature	°C	22–28	With air-conditioning (summer)
			16–24	With heating (winter)
	Relative humidity	%	40–80	With air-conditioning (summer)
			30–60	With heating (winter)
			0.3	With air-conditioning (summer)
Air velocity	m/s	0.2	With heating (winter)	
		30 ^a		
Chemical	Amount of fresh air	m ³ /(h · person)	30 ^a	
	Sulfur dioxide (SO ₂)	mg/m ³	0.50	1-h average
	Nitrogen dioxide (NO ₂)	mg/m ³	0.24	1-h average
	Carbon monoxide (CO)	mg/m ³	10	1-h average
	Carbon dioxide (CO ₂)	%	0.10	24-h average
	Ammonia (NH ₃)	mg/m ³	0.20	1-h average
	Ozone (O ₃)	mg/m ³	0.16	1-h average
	Formaldehyde (HCHO)	mg/m ³	0.10	1-h average
	Benzene (C ₆ H ₆)	mg/m ³	0.11	1-h average
	Toluene (C ₇ H ₈)	mg/m ³	0.20	1-h average
	Xylenes (C ₈ H ₁₀)	mg/m ³	0.20	1-h average
	Benzo(a)pyrene (B(a)P)	ng/m ³	1.0	24-h average
	Inhalable particulate matter (PM ₁₀)	mg/m ³	0.15	24-h average
	Total volatile organic compounds (TVOC)	mg/m ³	0.60	8-h average
Biological	Bacteria total	cfu/m ³	2,500	Depending on instrument
Radioactive	Radon (Rn)	Bq/m ³	400	Annual average (action level ^b)

^aRequirement for the amount of fresh air: \geq standard value; requirements for other parameters except temperature and relative humidity: \leq standard value

^bRecommended to introduce interventions to reduce the indoor concentration of radon when the standard value is reached

Tables 13 and 14 [64]. The “Hygienic assessment norm for central air-conditioning and ventilation systems in public places” prescribes the requirements of hygienic assessment of the new, reconstructed, extended, or running central air-conditioning and ventilation systems in public places. The purposes, references, contents, and methods of preventive and regular hygienic assessment are provided in the norm. The “Cleaning norm for central air-conditioning and ventilation systems in public places” prescribes the requirements of cleaning methods, cleaning process, performance and security of cleaning, and cleaning agencies and devices for the main parts of air-conditioning and ventilation systems in public places. Implementation of these norms has greatly improved the hygienic conditions of air-conditioned indoor environments in China.

Table 13 Hygienic requirements for air supply [64]

Parameter	Requirement
PM ₁₀	≤0.08 mg/m ³
Bacteria	≤500 cfu/m ³
Fungi	≤500 cfu/m ³
Pathogenic microorganisms	Not detectable

Table 14 Hygienic requirements for inner surface of air ducts [64]

Parameter	Requirement
Dust	≤20 g/m ²
Pathogenic microorganisms	Not detectable
Bacteria	≤100 cfu/cm ²
Fungi	≤100 cfu/cm ²

On the whole, a primary regulation and standard system for preventing and controlling indoor air pollution has been established through many years of endeavors in China. Indoor air pollution can be controlled from the beginning of building design, during building construction and decoration, and through proper maintenance of air-conditioning and ventilation systems. Meanwhile, the increasing requirements for better IAQ as well as advancement in IAQ research will help improve the regulation and standard system continuously during practical applications.

3.2 *Strengthening Research on Indoor Air Pollution and Its Control*

Besides promoting the establishment and improvement of IAQ-related regulations and standards, the Chinese government has also been very active in organizing and supporting the research on indoor air pollution and its control. Under the 10th National Five-Year Plan, the Ministry of Science and Technology of the People's Republic of China developed grants for three projects under the National Key Technologies R&D Program: "Evaluation technologies of health hazards of key indoor air pollutants," "Control technologies of health hazards of key indoor air pollutants," and "Control technologies of indoor air pollution from coal burning." These studies provided important technical support for evaluation and control of indoor air pollution.

As the "Outline of the National Program for Mid- and Long-Term Science and Technology Development (2006–2020)" requires to develop technologies for improving urban living and indoor environments, research on indoor air pollution and its control has been greatly strengthened and conducted in a more systematic way in China since 2006. The research contents and objectives of three major projects implemented during the 11th Five-Year Plan period are briefly described as below.

1. Research and development of environment-friendly building materials and products

As a source control strategy, the use of environment-friendly building materials and products can prevent indoor air pollution caused by building materials. In order to guide, regulate, and promote the research, development, production, and application of environment-friendly building materials and products, the Ministry of Science and Technology of the People's Republic of China organized and supported the "Research and development of environment-friendly building materials and products" as a key project of the National Key Technologies R&D Program.

The project mainly focused on research of production and application technologies, regulations and standards, and technical and economic policies related with environment-friendly building materials and products, aiming at mastering key common technologies of building material industry, developing key technologies and equipment with independent intellectual property rights for production and application of environment-friendly building materials and products, and achieving "leapfrog" development by widely promoting the application of environment-friendly building materials and products. It also aimed to establish a research, development, and production base and a technological innovation system for environment-friendly building materials and products by promoting the partnership of industry-university-research institute, integrating the technologies, and building demonstration production lines. Implementation of this project would provide technical support and safeguard measures for research, development, production, application, and operation management of green building materials and products in China.

2. Key technologies for improving and ensuring the quality of urban living environments

The living environment greatly affects people's quality of life, health, and productivity. It is an important indicator of a country's or region's economic development and living standards and also an important part of the key technology system for sustainable development of construction industry. In order to improve the quality of living environments to improve people's quality of life, a major project of the National Key Technologies R&D Program, "Key technologies for improving and ensuring the quality of urban living environments," was launched by the Ministry of Science and Technology of the People's Republic of China.

The major goal of the project was to realize the "leapfrog" development of the key technologies for improving and ensuring the quality of urban living environments by developing key technologies and complete sets of equipment with independent intellectual property rights and formulating and improving regulations and standards related with urban living environments. Based on technology integration and demonstration, the project was expected to establish a research and development base and an independent innovation system for technologies of improving and ensuring the quality of urban living environments.

3. Key technologies and equipment for removal of typical indoor air pollutants

As one of the most serious environmental problems in China, indoor air pollution in public places has gathered growing concern in recent years due to its adverse effects on human health and quality of life and work. In order to meet major demands of indoor air pollution control for large public places (e.g., supermarkets, shopping malls, places of entertainment), the Ministry of Science and Technology of the People's Republic of China provided financial supports for a key project under the National High-Tech R&D Program (863 Program), i.e., "Key technologies and equipment for removal of typical indoor air pollutants."

The overall objective of the project was to develop technologies for analyzing and regulating typical indoor air pollutants (organic pollutants and harmful microorganisms) in public places, provide new cleaning materials and technologies with independent intellectual property rights, manufacture cleaning function modules, develop and demonstrate new independent air cleaners and air cleaning prototype units for central air-conditioning systems, establish an indoor air cleaning technology system, and provide support for boosting the technical level of indoor air cleaning technologies and equipment and improving the IAQ of public places in China.

In summary, China has conducted large amounts of research work on indoor air pollution and its control over the past two "Five-Year Plan" periods and has realized "leapfrog" progress in improving IAQ by developing and applying new technologies, materials, and equipment. According to the "National 12th Five-Year Program for the Science and Technology Development," China will further push forward the research, development, and industrialization of indoor air cleaning technologies and equipment during the 12th Five-Year Plan period.

3.3 Developing Indoor Environmental Monitoring and Cleaning Industry

The indoor environmental monitoring and cleaning industry emerged in the 1980s in China and has grown at a rapid pace since 2000 along with the occurrence of serious indoor air pollution due to interior decoration and refurbishment, the increasing public awareness of the importance of IAQ, the promulgation and implementation of several national standards concerning IAQ, and the progress in research on indoor air pollution and its control. A relatively complete industrial system of indoor environmental monitoring and cleaning has formed in China, including air cleaners, air cleaning materials, air cleaning systems, indoor decorating and refurbishing materials with cleaning function, fresh air ventilation systems, and indoor environmental pollution monitoring, control, and evaluation systems. Statistics indicate that the scale of the indoor environmental protection (mainly monitoring and cleaning) industry has been growing with a compound annual growth rate of 28% in recent years, reaching 30 billion yuan in 2008 [65].

In view of the current status and future trends of indoor air pollution in China, demand for indoor environmental monitoring and cleaning will continue to grow in the coming years, requiring further development of the indoor environmental monitoring and cleaning industry. On the other hand, as an industry with high technology content, technical level of the indoor environmental monitoring and cleaning industry determines its capability of providing new types of services and products quickly in response to market needs. In order to boost the innovation capacity of enterprises engaged in indoor environmental monitoring and cleaning to facilitate technical upgrading, the Chinese government has been greatly promoting the partnership of industry-university-research institute in research, development, and industrialization of new technologies and equipment, which will undoubtedly help enhance the overall development of the industry.

4 Major Problems in Current Indoor Air Pollution Control

Despite the great progress in indoor air pollution control in China, there are still some problems which limit the effectiveness of pollution control measures, including lack of mandatory standards for IAQ, lack of regulation and labeling of pollutant emissions from indoor decorating and refurbishing materials, lack of an effective performance evaluation system for air cleaning products, and lack of proper maintenance of air cleaners.

4.1 Lack of Mandatory Standards for Indoor Air Quality

GB/T 18883-2002 “Indoor air quality standard” has been implemented for nearly 10 years in China and has played significant roles in preventing and controlling indoor air pollution and safeguarding people’s health. As a standard with no mandatory enforcement mechanism, however, GB/T 18883-2002 is not binding for either building developers or renovation contractors. Although GB 50325 “Code for indoor environmental pollution control of civil building engineering” stipulates mandatory acceptance criteria for indoor environmental quality of newly constructed, extended, or renovated civil building engineering, it does not apply to civil buildings delivered to users. Moreover, passing the acceptance inspection required by GB 50325 does not mean or provide assurance for good IAQ during the normal use of civil buildings. On the one hand, inadequate ventilation and/or introduction of new pollution sources such as furniture and chemical household products can increase the indoor pollutant concentrations. On the other hand, many other pollutants besides those included in GB 50325 (radon, formaldehyde, benzene, ammonia, and TVOC) can also deteriorate the IAQ and cause adverse health effects.

4.2 Lack of Regulation and Labeling of Pollutant Emissions from Indoor Decorating and Refurbishing Materials

Although GB 18580 and GB 18587 include pollutant emission limits for wood-based panels and finishing products and carpets, carpet cushions, and adhesives, national standards for other indoor decorating and refurbishing materials (GB 18581–18586) prescribe content limits of the regulated harmful substances. The contents of harmful substances determine the potential of materials (products) to cause indoor air pollution but not the actual indoor air pollution level due to the lack of correlation between the contents and the emission features of harmful substances. As a result, the current labeling system for indoor decorating and refurbishing materials, mainly based on the contents of harmful substances, is not effective enough in guiding the selection of indoor decorating and refurbishing materials to control indoor air pollution at its source, explaining why the IAQ of some newly renovated buildings fails to meet the state standards although all the decorating and refurbishing materials (products) used conform to the corresponding national standards.

4.3 Lack of an Effective Performance Evaluation System for Air Cleaning Products

Both the type and quantity of air cleaning products on the market have been significantly increasing in recent years in China due to the rapid development of indoor air cleaning industry. Effective performance evaluation of air cleaning products is the base for regulating the market and promoting the development of better performing products. At present, however, no performance evaluation for air cleaning materials is being conducted due to the lack of relevant regulations and standards. Although a recommendatory national standard GB/T 18801-2002 “Air cleaner” was promulgated by the General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China in 2002 and revised in 2008 (GB/T 18801-2008), they have played very limited roles in regulating the air cleaner market and guiding the consumers to choose appropriate air cleaners because the involved performance evaluation indices, cleaning efficiency of pollutants (GB/T 18801-2002), and clean air delivery rate (CADR) per unit of energy consumption (GB/T 18801-2008), cannot reflect the applicability or the actual CADR of air cleaners. Besides, the current evaluation of air cleaners has not taken the production of possible hazardous byproducts except O₃ (included in the building industry standard JG/T 294-2010 “Test of pollutant cleaning performance of air cleaner”) into consideration.

4.4 Lack of Proper Maintenance of Air Cleaners

As the most important type of air cleaning products, air cleaners have become more and more popular in urban Chinese households. The domestic sales volume of air

cleaners increased from 400 thousand units in 2006 to 1 million units in 2010 [12]. Since filtration and adsorption are the commonly used air cleaning technologies in air cleaners, periodical cleaning and/or replacement of the filtration and adsorption materials are required to ensure the cleaning performance of cleaners. Non-/improperly maintained equipment will lose its cleaning capability or even cause secondary indoor air pollution by releasing trapped pollutants back into the air. At present, however, neither the air cleaner production enterprises nor any special agencies in China provide specialized maintenance service for air cleaners, which absolutely discourages the promotion use of air cleaners and obstructs the development of air cleaner industry.

5 Concluding Remarks

Indoor formaldehyde pollution has been effectively alleviated in recent years in China by limiting the formaldehyde emission of wood-based panels and finishing products used in indoor decoration and refurbishment. Although indoor pollution of benzene has been effectively reduced through forbidding the use of benzene as solvents and diluents for coatings and adhesives that are intended for indoor use, indoor pollution of toluene and xylenes still exists. Serious outdoor pollution of PM, poor maintenance of air-conditioning systems, and the increasing use of materials and products containing plasticizers and flame retardants are major causes of indoor pollution of PM, biological pollutants, and SVOCs in China, to which more attention should be paid in the future.

Great progress in indoor air pollution control has been achieved in China through many years of efforts on formulating and improving IAQ-related regulations and standards, strengthening research on indoor air pollution and its control, and developing indoor environmental monitoring and cleaning industry. However, there are still some problems in the current control of indoor air pollution, including lack of mandatory standards for IAQ, lack of regulation and labeling of pollutant emissions from indoor decorating and refurbishing materials, lack of an effective performance evaluation system for air cleaning products, and lack of proper maintenance of air cleaners. These problems should be addressed as soon as possible to ensure the effectiveness of pollution control measures.

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