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Impacts of Household Coal and Biomass Combustion on Indoor and Ambient Air Quality in China: Current Status and Implication

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HIGHLIGHTS

- Contributions of CO, $PM_{2.5}$, BC, and PAHs emissions from household combustion more than one-third.
- Relative contributions of $PM_{2.5}$ and BC in poor regions are four times higher than that in rich regions.
- Chimney can reduce indoor $PM_{2.5}$ level to be about 20% when burning dirty solid fuels in stoves.
- $PM_{2.5}$ exposure level of housewives is about 2~4 times of that of adult men in poor rural regions.
- $PM_{2.5}$ and BC EFs increase with solid fuel volatile matter content and up to ~100 times difference.

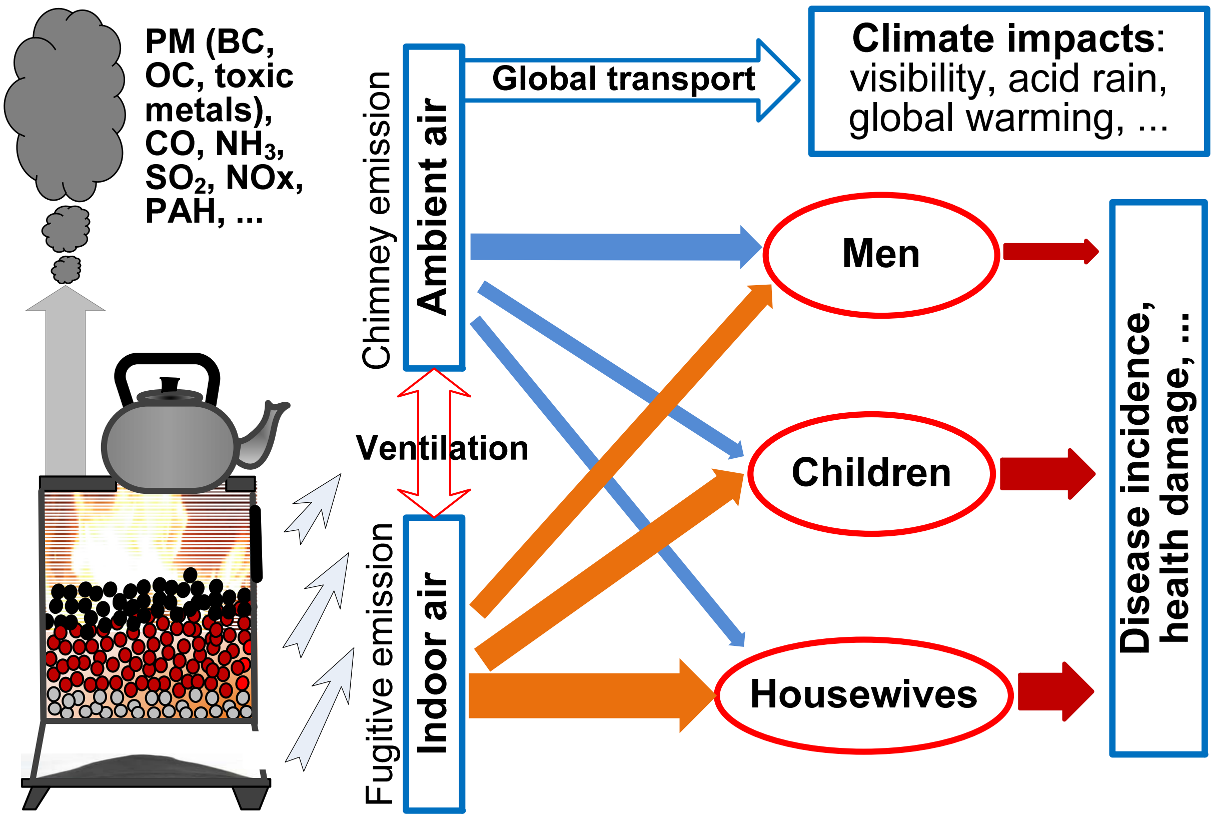
ABSTRACT

This review briefly introduces current status of indoor and ambient air pollution originating from household coal and biomass combustion in mainland China. Owing to low combustion efficiency, emissions of CO, $PM_{2.5}$, black carbon (BC), and polycyclic aromatic hydrocarbons have significant adverse consequences for indoor and ambient air qualities, resulting in relative contributions of more than one-third in all anthropogenic emissions. Their contributions are higher in less economically developed provinces, such as Guizhou (61% $PM_{2.5}$, 80% BC), than that in more developed ones, such as Shanghai (4% $PM_{2.5}$, 17% BC). Chimneys can reduce ~80% indoor $PM_{2.5}$ level when burning dirty solid fuels, such as plant materials. Due to spending more time near stoves, housewives suffer much more (~2 times) $PM_{2.5}$ than the adult men, especially in winter in northern China (~4 times). Improvement of stove combustion/thermal efficiencies and solid fuel quality are the two essential methods to reduce emissions. $PM_{2.5}$ and BC emission factors (EFs) have been identified to increase with volatile matter content (V_d) in traditional stove combustion. EFs of dirty fuels are two orders higher than that of clean ones. Switching to clean ones, such as semi-coke briquette, was identified to be a feasible path for reducing >90% $PM_{2.5}$ and BC emissions. Otherwise, improvement of thermal and combustion efficiencies by using under-fire technology can reduce ~50% CO_2, 87% NH_3, and 80% $PM_{2.5}$ and BC emissions regardless of V_d. However, there are still some knowledge gaps, such as, inventory for temporal impact of household combustion on air quality, statistic data for deployed clean solid fuels and advanced stoves, and effect of socioeconomic development. Additionally, further technology research for reducing air pollution emissions is urgently needed, especially low cost and clean stove when burning any solid fuel. Furthermore, emission-abatement oriented policy should base on sound scientific evidence to significantly reduce emissions.

Keywords:

Particulate matter emissions, coal burning emissions, household stove, human exposure, air quality control, pollution emissions from solid fuel combustion

GRAPHIC ABSTRACT



CONTENTS

1. Introduction

Solid fuel combustion for heating and cooking was a source of energy used by early hominids from about 1.6 million years ago (James, 1989; Roebroeks and Villa, 2011). The controlled use of biomass combustion has been commonly seen as a breakthrough adaptation in human evolution (Brown et al., 2009). The controlled fire offered human a survival advantage through cooking and heating, as well as protecting people from attacks from predatory species in China for around the last 0.5 million years (James, 1989; Perez-Padilla et al., 2010). The earliest indoor air quality problems may have been caused by the use of fires inside stone-age dwellings. People brought air pollutants into the indoor living space and breathed in pollutants. Early humans may have identified that poor air quality was principally a problem in the indoor environment, resulting in early attempts to mitigate these problems through ventilation (Matson and Sherman, 2004). The Banpo villagers in China incorporated chimneys into houses to remove the products of combustion used for heating, lighting or cooking from around 4000-5000 Before Christ (Li and Jones, 2000). The living environment has been changed over the past 10,000 years, while household combustion has also evolved via improving stove structure and cooking vessels. Additionally, various solid fuels have been employed for combustion in Chinese households, mainly including biomass in the form of wood, dung and crop residues, as well as coal since approximately 220 AD. Figure 1 shows a brief illustration of the developments related to household solid fuel combustion.

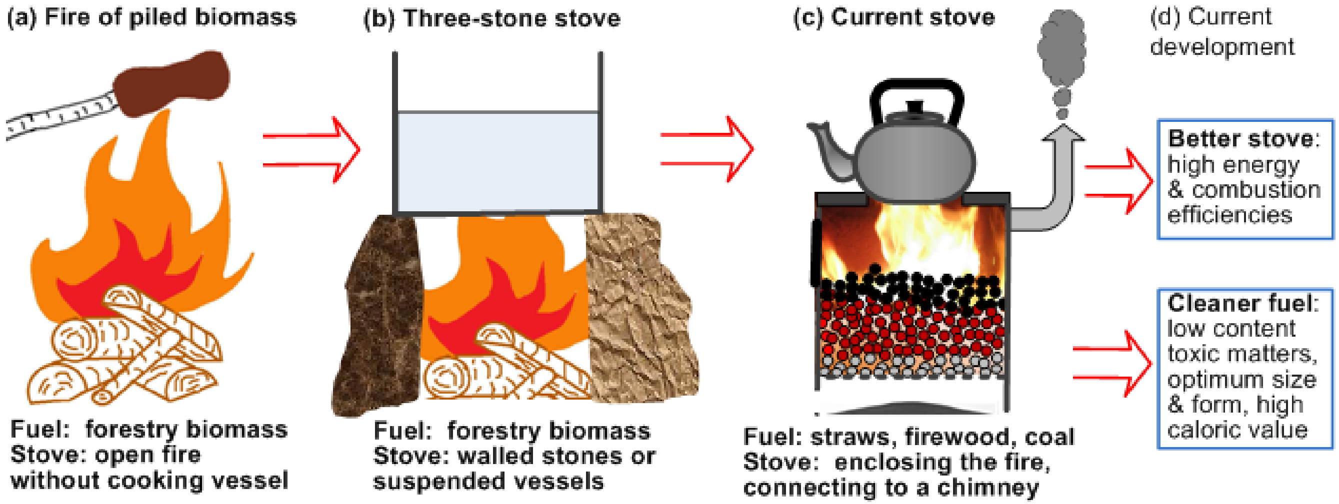


Fig. 1. Brief illustration of the development for household solid fuel combustion from the hominid time to the current status.

Why pollutant species are released during household solid fuel combustion? Ideally, complete combustion of fuels containing carbon, hydrogen, and oxygen should only produce CO_2 and H_2O. However, in reality we know that complete combustion is impossible, as household stoves are not ideal combustors and the fuel used is in bulk form which may limit the combustion rate and the amount of oxygen available. In a substoichiometirc environment, the incomplete combustion likely results in the production of carbon monoxide (CO), volatile organic compounds (VOCs), polyaromatic hydrocarbons (PAHs), and particulate matter (PM). We must also consider the formation of nitrogen oxides (NO_x) if the combustion temperature is high enough, or there is nitrogen element present in the solid fuel (e.g. coal). In general, solid fuels contain nitrogen (N) and sulphur (S), as well as a number of mineral elements, including; Al, Si, Ca, Fe, K, Mg, Na, and P, and a number of potentially toxic trace materials (e.g., As, Pb, Hg, Mn, Cd, Co, and Cr). Table 1 lists the overall features of elemental concentrations in Chinese biomass and coals, and this list suggests that Chinese solid fuels always contain the most significant and toxic trace elements, as well as nitrogen and sulphur. Even if the ideal stove were to be used to burn them, sulfur dioxide (SO_2) and NO_x would still be released and mineral elements including toxic ones would also be released in gaseous and/or particulate-bound states. Given the incomplete nature of the combustion in household stoves, we must also consider the formation and/or release of other nitrogenous compounds, such as NH_3, and the emission of elemental/organic carbon (EC/OC). These processes are briefly summarized in Fig. 2. Emitted PM, toxic metals, NH_3, and PAHs are harmful to the health of exposed people, while the global climate is also impacted, such as that SO_2 and NO_x are precursors to acid rain, NO_2 and reactive organic gases precursors to ozone. Thus indoor and ambient air qualities are closely related to the household solid fuel combustion.

Table 1. Characteristics of Chinese biomass (crop residue and firewood) and coals. These values were summarized and averaged from 12 types of agricultural biomass (including rice straw, wheat straw, corn stalk, and cotton stalk), 9 types of forestry biomass (including birch, spruce, and willow), and 3 types of coals from the previous report (Liao et al., 2004), while the listed major mineral elements were obtained from another report (Dai et al., 2012). A_d, V_d, FC_d, and $S_{t,d}$ indicate the ash, volatile matter, fixed carbon, and total sulfur contents on a dry basis, respectively, while M and Q indicate the moisture content and net calorific value, respectively.

Composition		Crop residue	Firewood	Coal
Proximate analysis	M (wt%)	8.3	8.3	2.8
	A_d (wt%)	8.6	4.4	20.1
	V_d (%)	66	71	28
	FC_d (%)	17	16	49
	Q (MJ/kg)	17	19	34
Ultimate analysis	C (%)	43	48	64
	N (%)	0.94	0.41	1.13
	O (%)	43.8	41.6	10.1
	H (%)	6.65	7.32	3.97
	S (%)	0.25	0.12	0.97
elements (%)	Al	0.20	0.06	3.17
	Si	0.007	0.001	3.95
	Ca	1.20	0.95	0.88
	Fe	0.24	0.16	3.40

	K	1.17	0.38	0.16
	Mg	0.39	0.13	0.13
	Na	0.14	0.02	0.12
	P	0.14	0.06	0.04
Trace mineral elements (μg/g)	Ni	5.0	15.3	13.9
	Pb	22.6	7.8	20.9
	V	3.7	1.6	76.5
	Cd	0.4	0.4	0.2
	Co	1.6	0.8	8.5
	Cr	7.2	8.6	36.8
	Cu	27.1	33.8	27.5
	As	1.3	0.7	14.5

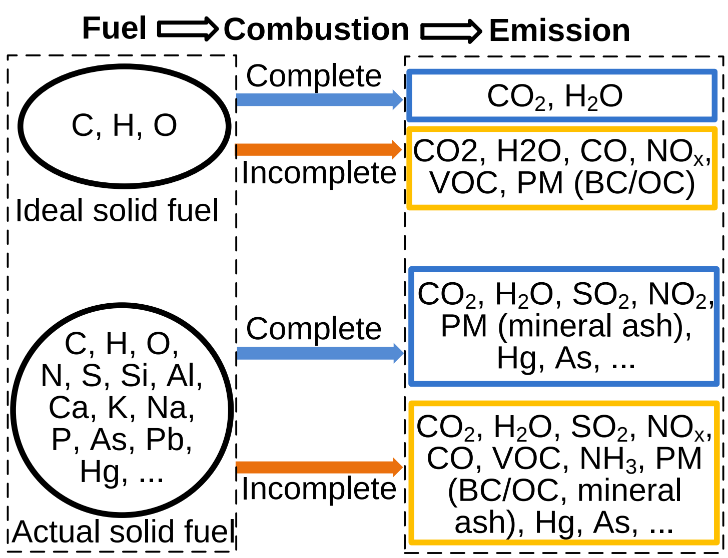


Fig. 2. Illustration of the pollutant emissions from complete and incomplete combustions of the cleanest (ideal) and actual solid fuels.

Why the indoor air pollution from household combustion has attracted an increasing concern in nowadays China? Household pollutant levels originating from the household solid fuel combustion is mainly determined by the fuel quality, stove technology (including body leakage, chimney quality, and combustion technology), and house ventilation (including air exchange rate with ambient air and other rooms) (Peabody et al., 2005). Other conditions such as ambient temperature and geographic variables should be taken into account for a detailed consideration of the potential determinants of exposure levels (Smith et al., 2012). The fuel quality and the stove technology have been gradually improving under the fast development of China's economy situation during the past several decades. Most rural buildings have been rapidly replaced by houses with reinforced concrete structure of increased airtightness and high use efficient of energy, however, some of the old sources of indoor air pollution that may not have been a problem under high ventilation rates are now creating problems (Matson and Sherman, 2004). Additionally, since per capital consumption ability increases with per capita income of rural family including rural-to-urban migrants, larger amounts of solid fuels are used. The per capital consumption of household coals, mainly used for heating in the northern part of the country, had increased from about 0.10 ton/person in 2001 to about 0.15 ton/person in 2013 in mainland China, see Fig. 3(a). Figures 3(b) and 3(c) suggest that coal and biomass are still widely used as residential solid fuels in mainland China. Residential coal has been mainly consumed in the household heating and coal supply regions, while biomass has been mainly used as residential cooking fuel in large agricultural and economic less economically developed regions.

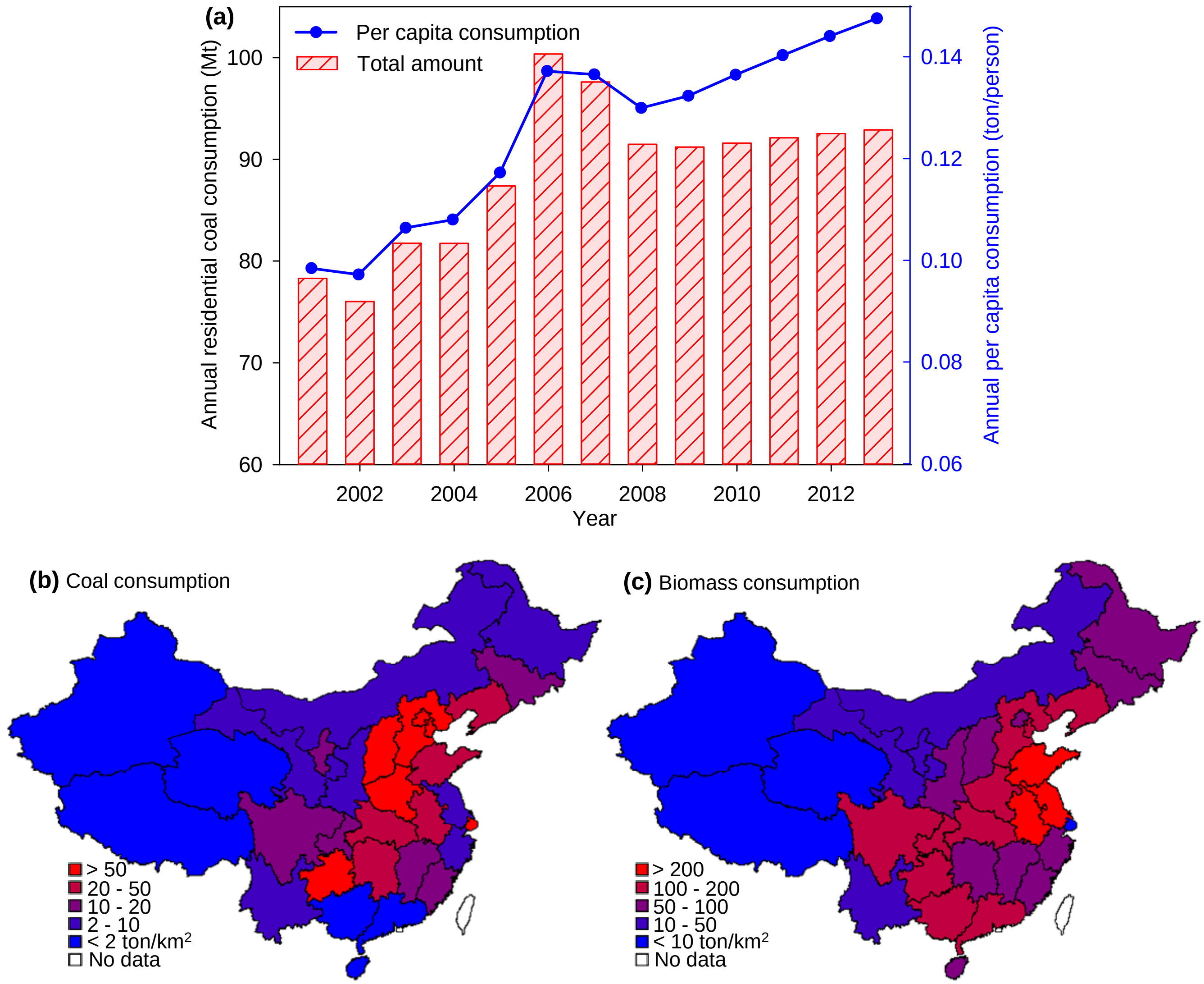


Fig. 3. (a) Annual residential coal consumption and per capital consumption during 2001-2013 in mainland China, and geographic distributions of residential (b) coal and (c) biomass consumption in mainland China in 2007. The amount of residential coal consumption was directly obtained from China energy statistical yearbook (NBSC, 2015), while per capital consumption value was the residential coal amount divided by rural population, including people living in rural and rural-to-urban migrants.

Why household combustion has been considered to be one of major anthropogenic contributors of atmospheric pollutants in contemporary China? As the China's population had grown from about 30 million in 221 Before Christ (China firstly unified) to 1.34 billion in 2010, the household combustion of biomass and coal has significantly increased, and thus, inevitably, the potential adverse impact of the household combustion on ambient air quality. In addition, severe haze pollution episodes have been frequently occurring in China over the past decade (Guo et al., 2014; Huang et al., 2014a). Pollution emitted from the household solid fuel combustion has been attracting increasing public concern, although the percentage of fuel consumed for household use compared to that used for all other activities including industrial combustion, is very low. Comparing to industrial boilers, household stoves often feature low thermal efficiency and very incomplete combustion without air pollution control device. For instance, emission factors (EFs) of primary $PM_{2.5}$ (PM of aerodynamic diameter equal to or less than 2.5 μm) from household coal combustion can be ~ 100 times higher than those from power plant coal boilers (Zhang et al., 2008). Figure 4 shows that the contribution of primary $PM_{2.5}$ emissions from the residential coal consumption to that from all coal consumption activities in China had increased from 27.5% in 2006 to 35.5% in 2010 (Wang et al., 2014d), although the ratio of consumed coal for the residential activity had decreased from 3.7% to 2.5%. It has been estimated that in China's annual anthropogenic emissions, about 36% of primary $PM_{2.5}$, 53% of EC, 62% of PAHs are from residential solid fuel combustion (Huang et al., 2014c; Shen et al., 2015; Shen et al., 2013b; Wang et al., 2012). Thus, the pollutant emission from the residential solid fuel use is a major anthropogenic source of the air pollution, while hundreds of the pollutant species are thought to increase health risk. The pollutants currently held to be the most important issue in China, including $PM_{2.5}$ of containing EC/OC and toxic trace components, CO, SO_2, NOx, NH_3, PAHs, and VOCs.

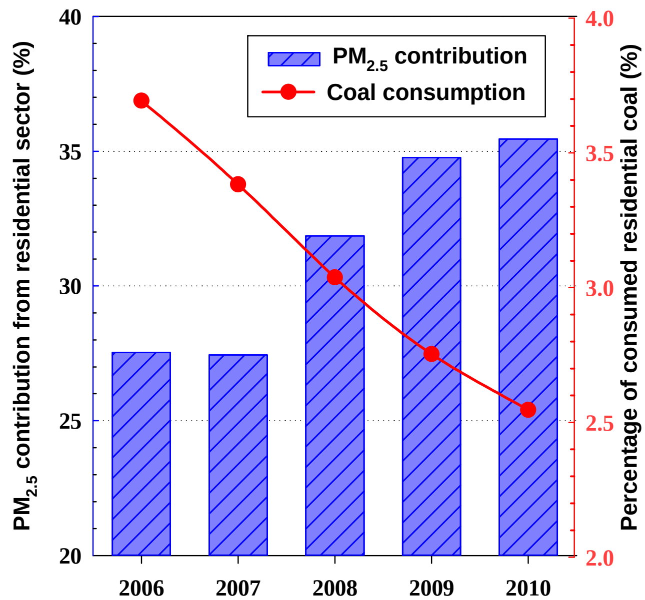


Fig. 4. The percentage of primary $PM_{2.5}$ emission from residential coal consumption in that from all coal consumption activities and the ratio of consumed coal for residential activity in mainland China during 2006-2010. *Data source*: China energy statistical yearbook (NBSC, 2015) and emission inventory (Wang et al., 2014d).

These pollutants affect both the indoor and the ambient air quality to a large extent, causing human health damage and climate change (Anenberg et al., 2013; Bond et al., 2013; Lim et al., 2013). Epidemiologic studies have confirmed that China's household air pollution can increase health risks, such as, respiratory symptoms, asthma, lung function reduction, lung cancer, neural tube defects, heart disease, elevated blood pressure, and immune system impairment. The household air pollution was also reported as leading to over one million premature deaths in China.

Pollutant emissions impacting on the ambient air quality will be firstly introduced by summarizing results from published emission inventories and source appointments. Impacts from major emitted pollutants on the indoor air quality will be analyzed including the consideration of the fuel/stove combustion and the household ventilation. An introduction of personal inhalation exposure level will be discussed. Aiming at reducing air pollution emissions, some knowledge gaps and implications for clean household fuel and stove technologies will be presented at the end.

2. Impacts on ambient air quality

Pollution emitted from major anthropogenic emission sources, including solid fuels burned in residential stoves and industrial boilers, as well as petrol and diesel burned in vehicles, is a regionally and globally atmospheric issue (Guo et al., 2014; Huang et al., 2014a). About 14 Mt of $PM_{2.5}$ and 2 Mt of black carbon (BC) were annually emitted to the atmosphere in China (Bond et al., 2004; Huang et al., 2014c; Wang et al., 2012). The emitted pollutants interact to produce a mixture of hundreds of different and hazardous chemicals known as secondary pollutants via physical processes and chemical reactions in the atmosphere. This process can cause a range of health outcomes such as respiratory illnesses including lung cancer (Wang et al., 2014e), as well as global climate changes including global warming, visibility decrease, and acid rain (Bond et al., 2013; Stocker et al., 2013).

Since 1980s, fast urbanization development in China leads to a decrease of household solid fuel user proportion, however, there are still approximately 43% (about 600 million people) and 30% of China's households utilized them for household cooking and heating in 2012, respectively (Duan et al., 2014). Household combustion using waste (see Fig. 1b) and traditional low efficient stoves is still a common practice in rural China. Owing to incomplete combustion without air pollution control devices, EFs of many pollutants for solid fuels burned in household stoves are two orders of magnitude higher than those burned in industrial boilers (Zhang et al., 2000; Zhang et al., 2008). About 98 Mt coal, 182 Mt firewood, and 340 Mt stalks in 2007 were burned in residential stoves in mainland China (NBSC, 2008). Figure 5 shows a typical photo for the winter morning in the suburb of Beijing which demonstrates that the household combustion in rural China is still a serious pollutant emission source and causes negative impact on locally ambient air quality. The contribution of pollutants from these residential solid fuel combustions to the local and regional air quality cannot be readily estimated owing to complex processes in the atmosphere and rare information on various pollution sources.

Fig. 5. Photograph taken in rural Beijing (Huairou village) at about 8:00 am on January 19th in 2016 (a winter morning), when the sun was rising and residents commonly added solid fuels in their household stoves to warm the cold morning and cook for their breakfasts.

Two major methods, *i.e.*, emission inventory and receptor model, have been commonly used to apportion sources of particles in China (Zhang et al., 2015). The emission inventory is based on the inventory of emission sources, while receptor models use marker species to estimate source contributions. The source appointment using the receptor model was firstly conducted by Blifford and Meeker in 1960s (Blifford and Meeker, 1967) and has been developed into several analysis methods, such as chemical mass balance and factor analysis including positive matrix factorization, principal component analysis, multi-linear engine, and unmix model (Henry and Christensen, 2010; Hu et al., 2010; Lang et al., 2013; Wang et al., 2009a; Zhang et al., 2012b). The source appointment method is now widely used for characterizing China's atmospheric PMs (Cao et al., 2005; Huang et al., 2014c; Huang et al., 2015; Wang et al., 2014a; Wang et al., 2009b; Wang et al., 2014f) and also showed that the household solid fuel combustion was a major contributor to the ambient PM level across the urban-rural spectrum (Wang et al., 2005), as well as that the relative PM and polycyclic aromatic hydrocarbon (PAH) contributions from the household solid fuel combustion are higher in heating-period than that in non-heating period in the northern China (Cao et al., 2005; Okuda et al., 2010; Tian et al., 2009; Wang et al., 2009b). However, there still lacks a systemic estimation of overall China and a detailed evaluation of pollutant emissions from the household solid fuel combustion. Thus the relative contribution of the residential solid fuel application to the ambient air pollution is introduced from the emission inventory in this section. In fact, owing to the limited information on pollutant EFs and actual distribution of fuel/stove combustions, the emission inventory is also so far not ideal on the accuracy for estimating the contribution of different sources.

Contributions of the household solid fuel combustion to the atmospheric pollutants will be introduced in this section. Basing on published inventories, we will firstly evaluate the contribution variety of different pollutant species. The major pollutants will be discussed in more detail on their historical contributions and geographical distributions at the province-level.

2.1. Contribution to atmospheric pollution

Although the ratio of household solid fuels in the total anthropogenic energy consumption is less than 15% recently in China (NBSC, 2008), relative contributions of pollutant emissions to the total anthropogenic emissions are significant. Lots of inventories report the residential emission amounts of different species, including primary anthropogenic CO_2, CO, NH_3, SO_2, NOx, 16 PAH (Sixteen priority PAHs identified by US Environmental Protection Agency in 1976), non-methane VOC (NMVOC), PM and its contained BC (Kang et al., 2016; Lei et al., 2011; Ohara et al., 2007; Shen et al., 2013b; Streets et al., 2003; Wang et al., 2014d; Xia et al., 2016; Zhang et al., 2009a; Zhang et al., 2007; Zhao et al., 2015; Zhao et al., 2011). On the basis of the recent and available inventory data, Figure 6 shows their relative contributions to the total anthropogenic emissions in mainland China. Relative contributions of NOx in 2010 and NH_3 in 2012 are both less than 5%, while CO_2 in 2014, and SO_2 and NMVOC in 2010 are in the range of 10% - 20%. The household solid fuel combustion contributes about 38%, 34%, 49%, and 58% of total anthropogenic emissions of CO in 2014, primary $PM_{2.5}$ and BC in 2010, and 16

PAHs in 2007, respectively. BC and the dominant ratio of 16 PAHs are in the particulate-bond state. This means that CO and PM are the most concerning pollutants. Comparing with other pollutants and especially CO_2, the high contributions of CO and PM are mainly attributed to the incomplete combustion in the household stoves, which commonly have lower combustion efficiency than industrial boilers. World Health Organization (WHO) also concerns on CO and $PM_{2.5}$ emissions and gives their recommendation values for health protection (WHO, 2014). Hereafter, this review will mainly focus on the emissions of CO, $PM_{2.5}$, BC, and PAH during the household solid fuel combustion.

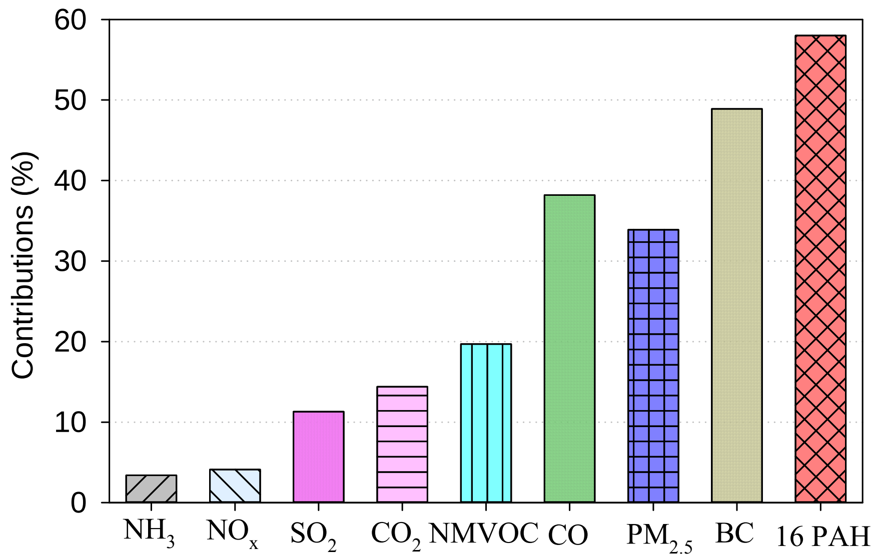


Fig. 6. Relative contributions of the residential solid fuel combustion to total anthropogenic emissions in mainland China. Data of CO_2 and CO in 2014 (Xia et al., 2016), NH_3 in 2012 (Kang et al., 2016), 16 PAH in 2007 (Shen et al., 2013b), and the other data in 2010 (Wang et al., 2014d) were adapted from publications.

Figure 7 shows annual emission amounts of CO, $PM_{2.5}$, and BC from residential solid fuel combustions, and their relative contributions to the total anthropogenic emissions in mainland China. Residential CO emission was in the range of about 60 ~ 70 Mt/year in the past decade, which suggests that more than 100 kg/(cap·yr) in view of per-capita emissions for household solid fuel users if the used amount value of residential solid fuels in the inventory was at the same accuracy for these years. The value was much higher than global average level of about 30 kg/(cap·yr) and developed countries of about 12 kg/(cap·yr). As shown in Fig. 3, the fuel per-capita consumption has continuously increased in the past decade, while the total coal consumption has also gradually increased, thus led to a continuous increase in CO emissions. However, the continuous economy growth in mainland China also results in the promotion of clean energy like natural gas and electricity, as well as cleaner household stoves. Thus, the household pollutant emissions are in race with the economy development, i.e., the increase per-capita consumption and the fast urbanization in mainland China.

Due to the fast urbanization and the deployment of clean fuels and stoves, the annual emission of $PM_{2.5}$, BC, and 16 PAH slightly decreased in the past decade, but their relative contributions to the total anthropogenic emissions have increased. The primary $PM_{2.5}$ contribution in the all anthropogenic emissions had increased from 31.7% to 33.9% during 2005-2010. This is due to the lack of air pollutant devices that can reduce emissions for household stoves. However, tremendous efforts have been made to reduce pollutant emissions from industrial boilers, such as requiring coal-fired power plants to install electrostatic and bag-filtering dust precipitators for reducing PMs (~ 100% in 2012) (Li et al., 2016c; Wang et al., 2014b; Wang and Hao, 2012; Wang et al., 2010b; Xu et al., 2009; Zhao et al., 2013).

The BC and PAH contributions from residential solid fuel combustions in the all anthropogenic emissions were both reported to be the largest anthropogenic contributor in mainland China (Shen et al., 2013b; Wang et al., 2014c; Wang et al., 2012; Wang et al., 2014d; Xu et al., 2006; Zhang and Tao, 2009). BC plays a unique and important role in the atmosphere by absorbing sunlight and emitting infrared radiation (Bond et al., 2013; IPCC, 2014). PAH has been well documented to have an adverse effect on human health and ecosystem (Gaspari et al., 2003). The significant EFs of BC and PAHs from the household solid fuel combustion have been widely investigated over the last decade in laboratory- and field-based experiments (Bond, 2002; Chen et al., 2015b; Chen et al., 2006; Chen et al., 2009; Li et al., 2007; Li et al., 2009; Lu et al., 2011; Ohara et al., 2007; Shen et al., 2014; Shen et al., 2013a; Shen et al., 2010; Wei et al., 2013; Wei et al., 2014; Zhang et al., 2009a; Zhang et al., 2008; Zhi et al., 2009). Inventories of BC and PAH for the residential solid fuel combustions have similar trends, which are in agreement with the results in Fig. 7 (Lei et al., 2011; Ohara et al., 2007; Streets et al., 2003; Wang et al., 2014c; Wang et al., 2014d; Zhang et al., 2009a; Zhao et al., 2015).

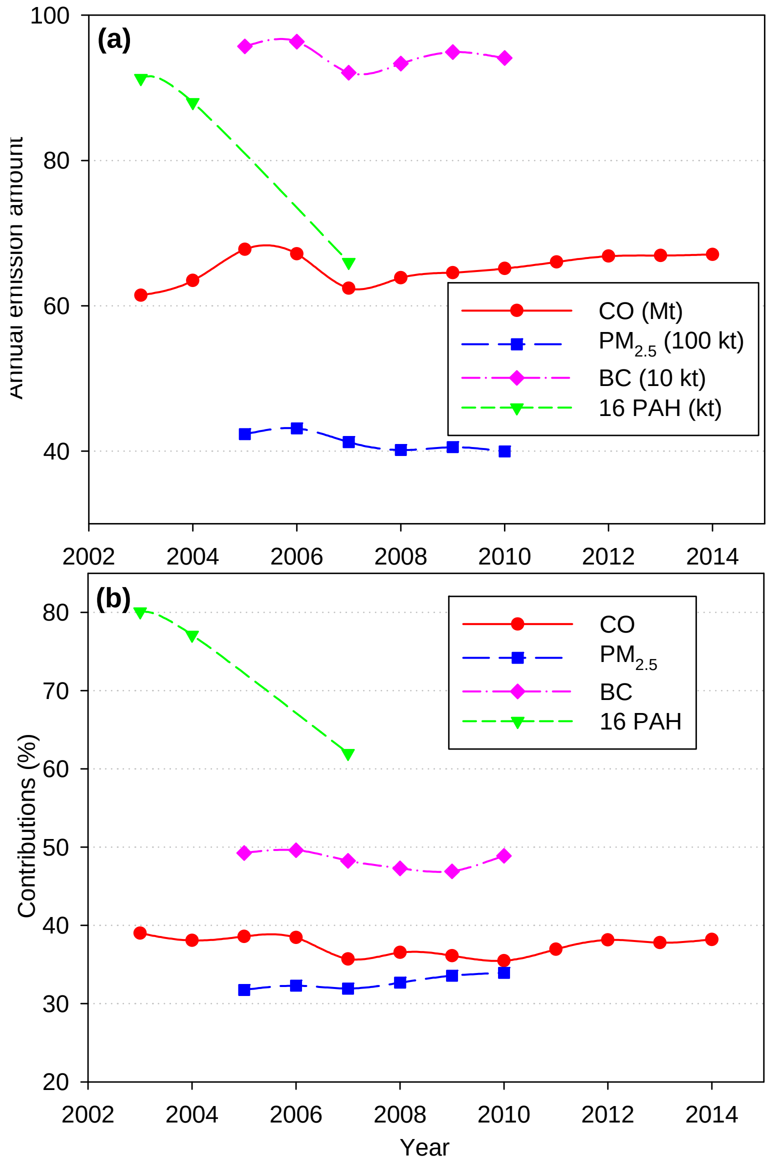


Fig. 7. (a) Annual emission amounts of CO, $PM_{2.5}$, BC, and 16 PAH from the residential solid fuel combustion, and (b) their relative contributions to the total anthropogenic emissions in mainland China.

Data of CO (Xia et al., 2016), $PM_{2.5}$ and BC (Wang et al., 2014d), 16 PAH in 2003 (Xu et al., 2006), 2004 (Zhang and Tao, 2009), and 2007 (Shen et al., 2013b) were adapted from different publications.

In general, the annual emission amounts of $PM_{2.5}$, BC, and 16 PAH from the residential solid fuel combustion have decreased gradually due to economy development, but their relative contributions to the ambient air pollutant have increased gradually in the past decade due to the strict pollutant control for industrial boilers. Although the estimation accuracy on pollutant inventories is still not perfect, the control of pollutant emissions from the residential combustion should attract more attention.

2.2. Geographical distribution of pollutant emissions

As discussed in the above subsection on the annual emissions, the difference of which among the historical period is mainly owing to the per-capita consumption and the urbanization. A remarkable influence is presented due to the imbalance of economic development in different regions, which leads to the difference for the ability of the per-capita consumption and the urbanization ratio. The replacement of raw solid fuels with clean energy in rural regions is difficult to achieve due to relative lower availability and higher price. The per-capita consumption amount of the household solid fuel in rural regions has increased during the economy or the urbanization development (see Fig. 3) (Duan et al., 2014). It is very difficult to distinguish the distribution of the household solid fuel in a certain province by using official statistical data (Ru et al., 2015). Here we only describe the difference among provinces in mainland China.

Figure 8 shows the geographical distribution of $PM_{2.5}$, BC, and 16 PAH emissions from the residential solid fuel combustion at the province level. Owing to no proper data for the geographical distribution of the CO emission, it was not included in this discussion. But the CO distribution is likely to be similar as that of $PM_{2.5}$. Sichuan province was the place with the highest contribution ratio among all provinces, followed by Shandong, Hebei, and Guizhou provinces. In Sichuan, relative ratios of $PM_{2.5}$, BC, and 16 PAH emissions are 8.9%, 7.5%, and 11.0%, respectively (Liu et al., 2007a; Wang et al., 2014d). The total relative ratios of $PM_{2.5}$, BC, and 16 PAH emissions from the four provinces are 27.1%, 27.9%, and 30.9%, respectively. All these provinces have with relatively low urbanization ratio and high population intensity, and thus consume relatively large amount of biomass and coals. For annual relative ratios of the household $PM_{2.5}$ and BC emissions, Guizhou province-the poorest province in China features the highest ratios for $PM_{2.5}$ and BC as 61.3% and 79.7% in 2010, respectively. Sichuan province features the second highest ratios as 53.2% and 67.2%. On the other hand, Shanghai-the richest city in mainland China features the lowest ratios for $PM_{2.5}$ and BC as 4.4% and 17.4% in 2010, respectively, while Zhejiang province-the richest province has the second lowest ratios as 12.4% and 22.6%. In general, the regions with winter heating (northern China) and less economically developed (southwest China) suffer higher pollutant impact from household solid fuel combustion than other regions in China.

In a brief summary, the household solid fuel combustion has significantly negative impact on the ambient air quality, especially on the emissions of CO, $PM_{2.5}$, BC, and PAH. Their emissions are mainly attributed to the low combustion efficiency of household stoves. According to the historical and geographical distributions of these species, their emission amounts and relative contributions are mainly determined by the urbanization development and the economy level.

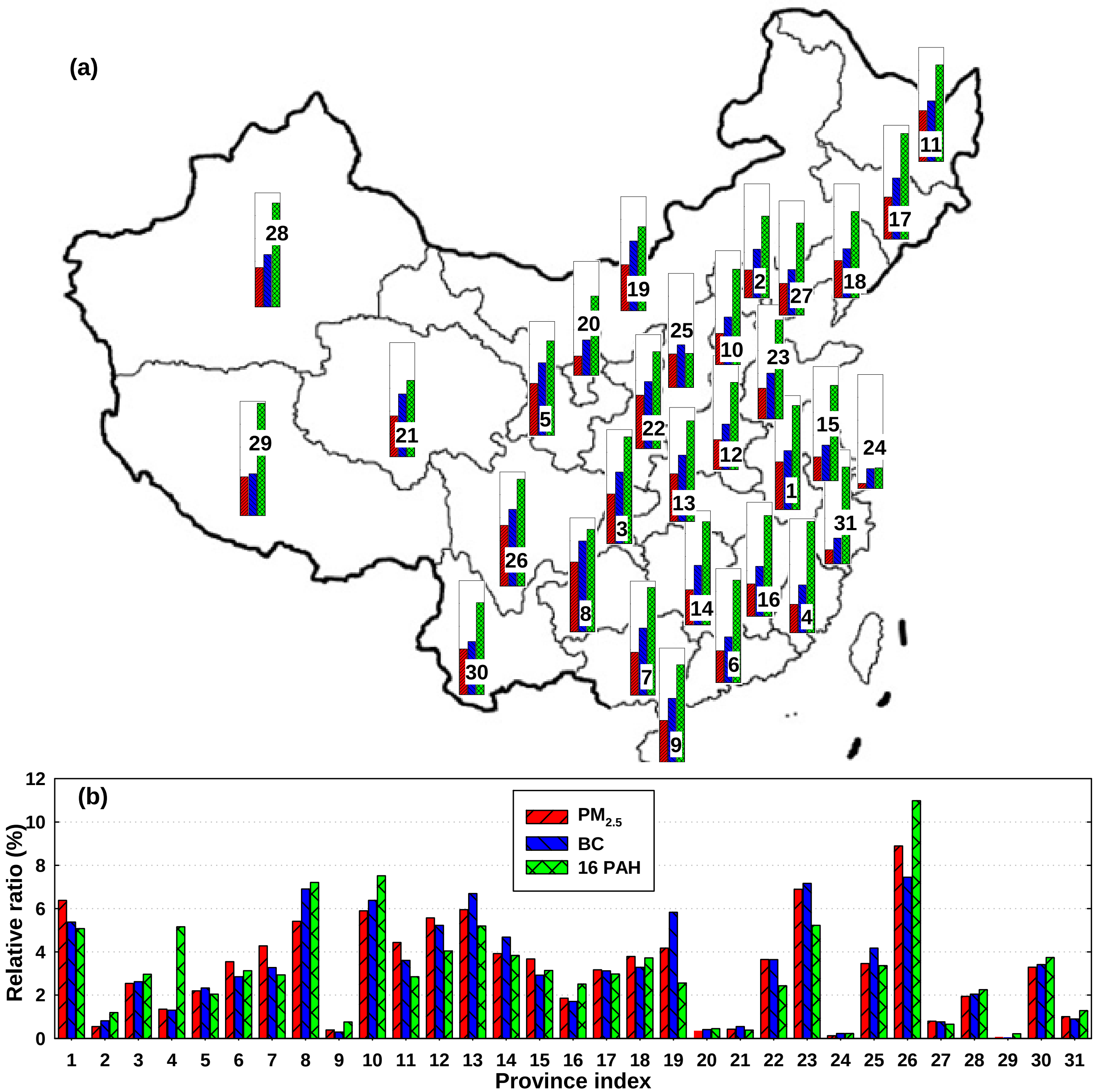


Fig. 8. (a) Relative contributions of $PM_{2.5}$, BC, and 16 PAH (in winter) from the residential solid fuel combustion to the total anthropogenic emissions in each province, and (b) relative ratios of each province in the total household $PM_{2.5}$, BC, and 16 PAH (in winter) emissions in mainland China. Province indexes are named as: 1 Anhui, 2 Beijing, 3 Chongqing, 4 Fujian, 5 Gansu, 6 Guangdong, 7 Guangxi, 8 Guizhou, 9 Hainan, 10 Hebei, 11 Heilongjiang, 12 Henan, 13 Hubei, 14 Hunan, 15 Jiangsu, 16 Jiangxi, 17 Jilin, 18 Liaoning, 19 Neimeng, 20 Ningxia, 21 Qinghai, 22 Shaanxi, 23 Shandong, 24

Shanghai, 25 Shanxi, 26 Sichuan, 27 Tianjin, 28 Xinjiang, 29 Xizang, 30 Yunnan, and 31 Zhejiang. Heights of the frame in each insert in (a) range from 0% to 100%. Data for $PM_{2.5}$ and BC is based on emissions in 2010 (Wang et al., 2014d), and while data for 16 PAH is based on emissions in 2003 (Liu et al., 2007a).

3. Impacts on indoor air quality

The indoor air quality is closely correlated with human health, with numerous studies linking exposure to combustion products from indoor stoves and/or heaters to a range of respiratory diseases, including lung cancer (Kim et al., 2015a; Kim et al., 2015b; Mumford et al., 1987; Smith et al., 2004). Due to the significant amount of time spent indoors (Perez-Padilla et al., 2010), the indoor air quality is a significant issue, particularly in regions which rely on the combustion of solid fuels for domestic cooking and heating applications (Smith et al., 2004). It has been found that levels of the air pollutants produced via combustion, such as PM_{10}, $PM_{2.5}$, VOCs and PAHs can vary with the fuel type and the stove type (Wang et al., 2010a; Wu et al., 2015a). Given that the direct combustion of solid fuels, such as coal and biomass, is relatively inefficient and that the rooms containing stoves/heaters are typically poorly ventilated, the potential for significant exposure is high.

The major determinant factors for the household air quality can be identified based on previous studies conducted in rural households in a number of Chinese provinces. Studies were conducted in Henan (Wu et al., 2015a), Guizhou (Alnes et al., 2014; Ma et al., 2015; Wang et al., 2010a; Zhang et al., 2012a; Zhang et al., 2014a), Shanxi (Chen et al., 2015a; Shen et al., 2013a), as well as a number of other studies conducted over larger areas (Mestl et al., 2007; Shen et al., 2010; Wei et al., 2014; Zhang et al., 2014b), e.g., Southwest China.

Despite significant interest in the indoor air quality, particularly in terms of the combustion of the solid fuel for heating and cooking applications, there is still a lack of detailed temporal data sufficient to draw conclusive conclusions about exposure more broadly. This is due in part to different measurement methods used across different studies, and the variation in fuel and stoves types used. There are also, significant regional differences in terms of housing design, behavior and climate, which serve to confound these issues.

Key factors which influence the composition and concentration of pollutants, were the fuel type and quality, the stove design (or material), the nature of any ventilation present, and/or layout of the household (Peabody et al., 2005). Seasonal variation in levels of indoor air pollutants have also been observed, with Wu et al. (2015a) noting that the combustion of solid fuels for heating purposes was only required for part of the year.

In the following sections we will consider the influence of fuel and stove type, ventilation and ambient conditions on indoor air quality.

3.1. Fuel and stove type

A number of solid fuel sources are utilized in China, together with a variety of stove designs which often vary regionally. Coal, wood, crop residue and dried manure are all materials that have been utilized for domestic heating and cooking applications, with the choice of solid fuels based on availability. Crop residue, for example, is a common fuel source utilized in Henan Province, due to the significant amount of agriculture present (Wu et al., 2015a). The type of stove used is also a significant factor, with metal, brick or clay stoves commonplace throughout the regions studied in the literature. It is also worth noting the usage of underground coal stoves in Shaanxi, as well as the use of fire pans, or open fires (though not widespread) in Gansu (Jin et al., 2006).

In their study of exposure level to indoor air pollutants, Jin et al. (2006) studied a number of households in 4 Chinese provinces (Gansu, Guizhou, Inner Mongolia and Shaanxi) considering fuels used for heating and cooking, as well as the stove type and the nature of any ventilation. In all regions the fuels predominantly used for cooking were either coal or biomass (wood or crop residue). Jin et al.

(2006) also noted the stove types used for cooking and heating, as well as noting differences between regions, for example, the majority of coal stoves in Guizhou, as simple metal enclosures with little or no ventilation. This is in contrast to biomass cooking stoves that were found to be made of brick or clay.

A number of authors have highlighted the absence of chimneys in many stoves, with Wang et al. (2010a) recording significantly higher levels of $PM_{2.5}$ and PM_{10} in households featuring stoves without chimneys. Jin et al. (2006) refer to stoves as “improved” or “unimproved” based on the presence or absence of a chimney, respectively. In the studies reviewed, levels of air pollutants were typically higher in households with “unimproved” stoves, however, the fuel type still played an important factor, with PAH levels found to be generally higher in households burning coal than in households burning crop residue (Wu et al., 2015a).

Zhang et al. (2000) tested 28 different fuel-stove combinations, with the objective of developing a database of EFs. While this work was more focused on environmental air pollution, it does serve to illustrate the variability in emissions from a range of fuel-stove combinations, which may be commonly found in China. Importantly, this study highlighted the low thermal efficiencies of biomass and coal stoves, and the resultant high levels of CO_2 and incomplete combustion products per unit of delivered energy (Zhang et al., 2000). The implication of this is significant, as not only does it highlights the comparatively high levels of pollutants in relation to other fuel sources, it also indicates that a much greater mass of fuel needs to be used to achieve the same energy.

In their study of particle emissions from rural households in Guizhou, Zhang et al. (2012) analyzed the composition of $PM_{2.5}$ emissions from wood and coal burning, reporting a significant amount of the composition is carbonaceous (55% for coal and 41% for wood). They also reported ratios of OC to EC of 7.6 for coal and 10.7 for wood, which were comparable to those obtained by Wang et al. (2010a) that also considered emissions from rural households in Guizhou.

Figure 9 illustrates the significance of the fuel type. In general, EFs of PM, BC, and PAHs are generally in the order of smokeless coal (briquette and chunk) < smoky coal (briquette and chunk) <

wood < brushwood/branch < crop residue (He et al., 2005). This is supported by the results of Hu et al. (2014) that found similar patterns were found for both measured indoor pollutant levels and personal exposures. Jin et al. (2006) also observed higher concentrations of particulate matter in households utilizing crop residue than those utilizing coal. The implication of a higher EF infers a higher pollutant emission. Figure 10 indicates the relationship between indoor pollutant concentrations of PAHs and the fuel type. However, some surveys for CO and NO_x concentrations indoors showed no distinct difference resulting from solid fuel types (Alnes et al., 2014; Edwards et al., 2007; Ma et al., 2015; Wu et al., 2015b; Zhang et al., 2014a).

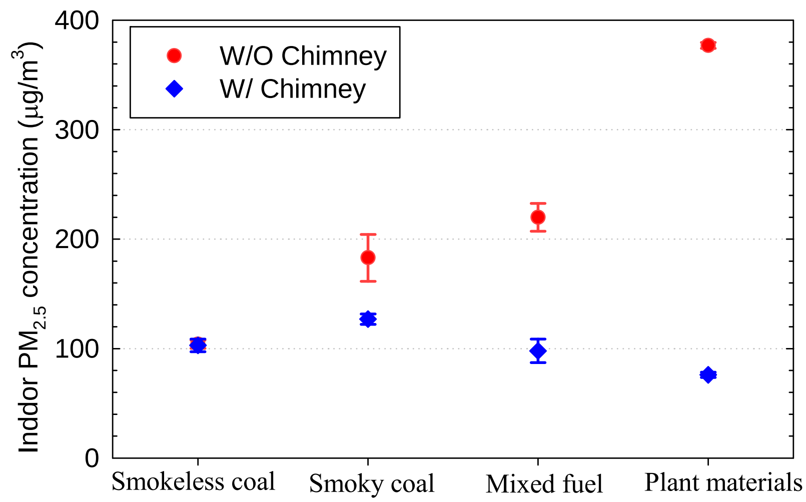


Fig. 9. Average indoor $PM_{2.5}$ ($\mu g/m^3$) concentrations from different houses related to stoves with (W/, vented) and without (W/O, unvented) a chimney for different solid fuel types, obtained from 24-hour continuous measurements in main living room for each sample. The mixed fuel is combinations of wood, plant materials and coal, where the plant materials include combinations of wood, tobacco stem, and corncob. Data source: the field study conducted in 30 villages from Xuanwei and Fuyuan counties in Yunnan province, in southwest of China (Hu et al., 2014).

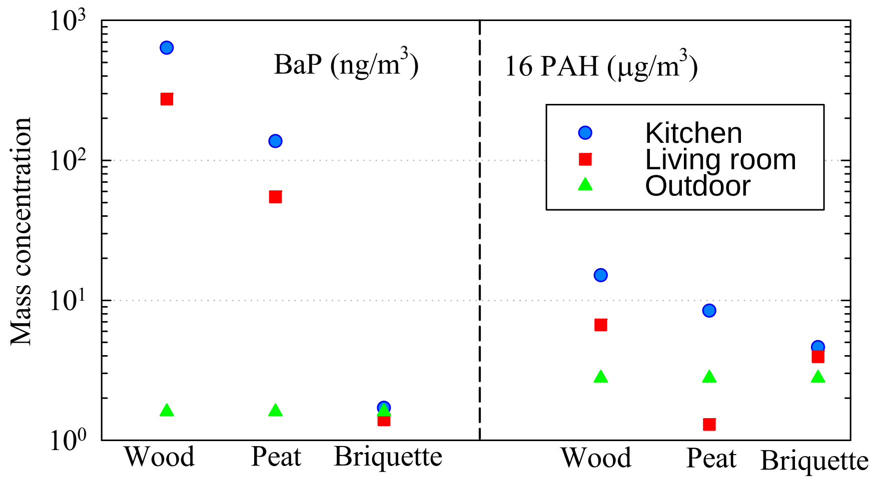


Fig. 10. Indoor BaP and 16 PAH concentrations related to fuel type and household location. Data source: the field study conducted in rural Shanxi province in summer (Chen et al., 2015a).

3.2. Household ventilation and layout

In the absence of a vented stove, the household ventilation is through windows and doors and is also influence by the presence of stairwells in the room, where the stove is located (Hu et al., 2014). It is expected that house layout will also influence pollutant levels indoors. Indeed, mixed effect modelling conducted by Hu et al. (2014) found that the number of windows was an important factor influencing the personal exposure to $PM_{2.5}$. Additionally, the ventilation through the poor sealing of walls and rooftops, in traditional households in rural parts of China, should also be considered.

In their study, Hu et al. (2014) found that households with one window in their main cooking area typically lead to a higher $PM_{2.5}$ exposure than those with zero (due to the aforementioned poor sealing of walls and rooftops in traditional homes) or two windows.

A number of households studied in previous work (He et al., 2005; Hu et al., 2014; Jin et al., 2006) have featured some form of chimney or flue duct. It has been observed that significantly lower levels of indoor pollutants are present when some forms of vented stoves were used (Hu et al., 2014), with corresponding reduced levels of the personal exposure also reported.

While the presence of a chimney will lead to reduced levels of pollutants in the room where the stove is located, this does not guarantee reduced exposure. A number of houses in Guizhou have been found to have chimneys that end in the attic (He et al., 2005; Jin et al., 2006), resulting in the highest concentrations of airborne pollutants in the home to be in the attic (He et al., 2005). The chimney ending in the attic appears to be limited to the Guizhou province, where the attic is used to dry food (He et al., 2005; Jin et al., 2006). In their study of 1741 household across 4 provinces, Jin et al. (2006) found chimneys were commonplace, however, in provinces such as Gansu and Guizhou, the chimney often did not go outside the house. In cases where the chimney did exit the house, over 90% of chimneys were below the height of the eaves (Jin et al., 2006). This raises the potential for pollutants to re-enter the house through the roof space.

Figure 9 shows indoor $PM_{2.5}$ concentrations related to household stoves, with and without chimneys, for different solid fuel types (Hu et al., 2014). According to the random-survey in rural Yunnan province, the reduced ratios for indoor $PM_{2.5}$ concentrations by the chimney were about 1%, 31%, 55%, and 80% for smokeless coal, smoky coal, mixed fuel, and plant materials, respectively (Hu et al., 2014). The reduction ratio is much higher for fuels with higher volatile matter content, which possess higher $PM_{2.5}$ EFs (Li et al., 2016b). In 2010, approximately 76% of stoves used for cooking in Guizhou did not feature a chimney (Alnes et al., 2014). Combustion in these household stoves generally resulted in higher indoor pollutant levels (Alnes et al., 2014; Armendariz-Arnez et al., 2010; Hu et al., 2014). In the absence of a chimney, often the only source of household ventilation is through open door and windows. There are times of the year, however, where the doors and windows will be close, which is likely the explanation for higher winter levels of indoor pollutants reported by Wu et al. (2015b). This will be discussed further in Section 3.3.

The location of stoves in households has also been shown to influence the pollutant concentrations (Alnes et al., 2014; Ding et al., 2012; Downward et al., 2014; Edwards et al., 2007; Fischer and Koshland, 2007; Gao et al., 2009; He et al., 2005; Hu et al., 2014; Jin et al., 2005; Ma et al., 2015; Shao et al., 2013; Zhang et al., 2014a; Zhong, 2011; Zhong et al., 2012). Typically, the concentration of pollutants in the living room is lower than that in the kitchen (stove location), as shown in Fig. 10 (Chen et al., 2015a). However, it should be noted that this relies on there being a clear demarcation between the rooms in the house and also assumes that only one stove is present. It has been noted in a number of studies that the kitchen and living room utilize the same space. Jin et al., (2006) for example found in their study that approximately 72% of households in Guizhou usually cook in the living room and that older homes in Inner Mongolia consisted of a large single room, which served as the living, cooking and sleeping space.

In cases where the household have multiple rooms, the levels of indoor air pollutants in bedrooms (where no heaters are present) are greatly dependent on dispersion, and heavily influenced by house layout (He et al., 2005). The exception to this is in the houses in Guizhou, with chimneys ending in the attic where, similar concentrations of pollutants were found in the bedroom (no heater) and the living room (heater), in some cases despite the presence of a door (He et al., 2005). In these cases it seems reasonable to conclude that the smoke is collecting in the attic and being distributed around the house (He et al., 2005) that is likely due to poor sealing between the rooms on the ground floor and the attic, a factor also noted by Hu et al. (2014).

Comparison of the studies by Hu et al (2014) and He et al. (2006), the province study indicates a large level of regional variation, in terms of house layout, stove type and fuel type. This serves to highlight the regional differences that make the results of individual studies, or region specific studies difficult to apply more broadly.

3.3. Ambient conditions

As well as considering the stove and fuel type and ventilation and house layout, some consideration must also be given to ambient conditions including outdoor air pollution, as well as seasonal and geographic factors, such as ambient temperature. Given that coal and biomass commonly used fuels for household heating applications, the ambient temperature is likely to be a significant influence on the indoor pollution levels and the exposure. Cold winters in the northern China typically result in significantly higher residential solid fuel (such as coal) consumption for heating than that in summers (Duan et al., 2014).

Households in Guizhou and Inner Mongolia, often utilize the household stoves in the living area for both cooking and heating purposes (Jin et al., 2006). In winter when in use for heating, the stoves will often be operating longer than when used for cooking alone, as may be the case in summer months. The duration of the period where household stoves are used for heating varies geographically, with Jin et al. (2006) noting that stove were used for 4-6 months in Gansu, 6-7 months in Guizhou, 6-7 months in Inner Mongolia and 5-6 months in Shaanxi.

Wu et al. (2015b) found higher levels of pollutants in households in Henan in winter than in autumn, with significantly higher pollutant levels ($PM_{2.5}$, PM_{10}) being recorded in living rooms in winter. A similar pattern has been observed by studies conducted in Hebei province, which reported higher concentrations of BC, OC and benzo-[a]-pyrene (BaP) in winter than in summer (Ding et al., 2012; Zhong, 2011; Zhong et al., 2012).

In addition to the higher pollutant levels typically observed in winter, consideration must also be given to other contributing factors. While higher pollutant levels in winter can be easily linked to higher fuel consumption (for heating), we must also consider any behavioral factors that may contribute. As previously noted, Wu et al. (2015b) observed that windows and doors which may be open to provide ventilation in summer, will be closed in winter to limit heat escape. This will have addition effect of keeping more pollutants indoor and potentially increasing exposure.

4. Impacts on personal inhalation exposure

The household solid fuel combustion is likely to be one of the largest emission sources of indoor air pollution in rural China, as well as an important source impacting on the ambient air quality, as described in the last two sections. Poor indoor and ambient air qualities can thus induce substantial exposure to air pollutants which mainly occurs inside the house since people spend more time indoors (Brauer et al., 2012). Exposure to these air contaminants can pose a serious health hazard, particularly for women, young children, and elders who typically spend much of their time inside the household (Bruce et al., 2000; Chafe et al., 2014; Lim et al., 2013; Mestl et al., 2007; Smith et al., 2009). Household air pollution has been estimated to be one of the main health risks worldwide such as respiratory and cardiovascular risks, including cancer. In addition, a recent report showed that poor indoor air quality accounts for 3.7% of total deaths in mainland China (GBD2010, 2013). The Chinese government is one of the first in the world to define a national health based indoor air quality (IAQ) standard for residences (Edwards et al., 2007). The standard for a 1-day average has been set at 150 µg PM_{10}/m^3, a level which still represents substantial health risks. Direct measurements of personal exposure to air pollutants in mainland China are extremely scarce (Baumgartner et al., 2011). In this section we introduce some results of the potential impact of fuel types, seasons, and geographic location on exposure levels to selected air pollutants among different population groups.

Figure 11 shows the effect of the fuel/stove combinations on the exposure levels to $PM_{2.5}$ among housewives (Hu et al., 2014). Similar is the effect on indoor $PM_{2.5}$ concentrations (see Fig. 9), from the combustion of solid fuels with a high volatile content which results in high $PM_{2.5}$ exposure levels, while combustion in stoves without chimney also leads to a higher $PM_{2.5}$ exposure level compared with stoves with chimney. This result is in consistence with the WHO recommendation, i.e., to use clean solid fuel such as processed coal for the household combustion (WHO, 2014).

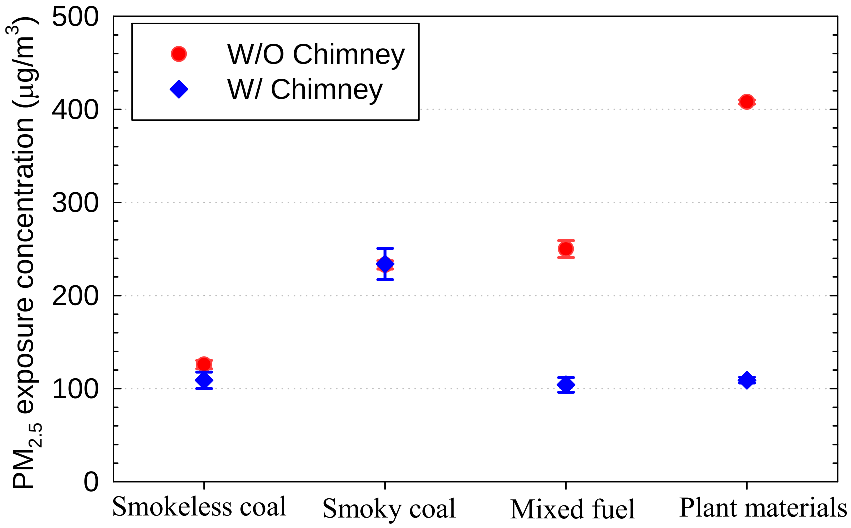


Fig. 11. Average concentrations of $PM_{2.5}$ of housewife exposure in different houses related to solid fuel type, as well as stoves installed chimney or not (see Fig. 9 caption for the explanation of mixed fuel and plant materials). The field studies were conducted in rural Yunnan province (Hu et al., 2014).

Other factors may also have effect on human exposure concentrations. Season can have an impact on exposure concentrations via household combustion activities, time spend inside the household, as well as the household ventilation. Figures 12 and 13 suggest that $PM_{2.5}$ and BaP exposure concentrations in winter are higher than in summer. In addition, the geographic location may also affect the exposure concentration. According to the reported indoor $PM_{2.5}$ levels from different provinces (Edwards et al., 2007; Jin et al., 2005), people in Northern China (Hebei province) are exposed to higher $PM_{2.5}$ concentrations than those who live in the southern China (Yunnan province) (Baumgartner et al., 2011; Huang et al., 2015; Zhong et al., 2012) (see Fig. 13).

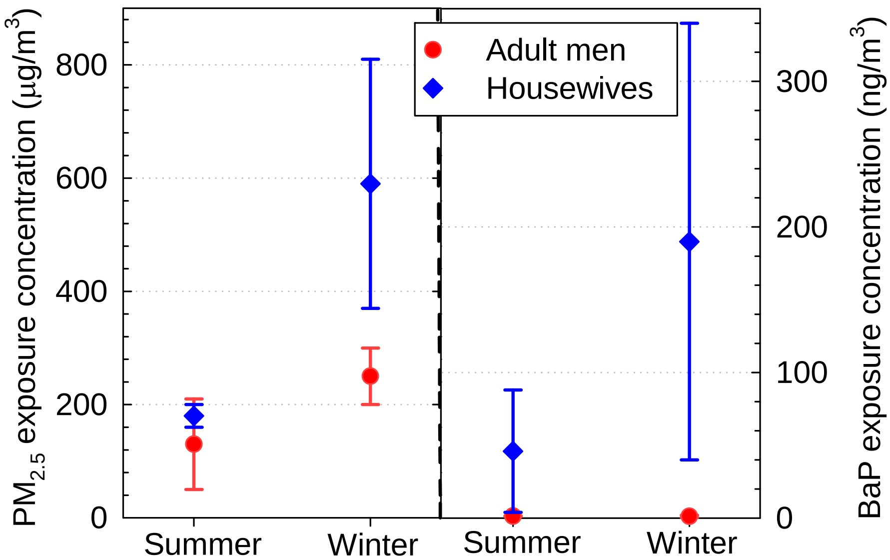


Fig. 12. Exposure concentrations of $PM_{2.5}$ and BaP. Housewives suffer much higher personal inhalation exposure levels than the adult men, especially in winter. Data was abtained from field studies in rural Hebei (Ding et al., 2012; Zhong et al., 2012).

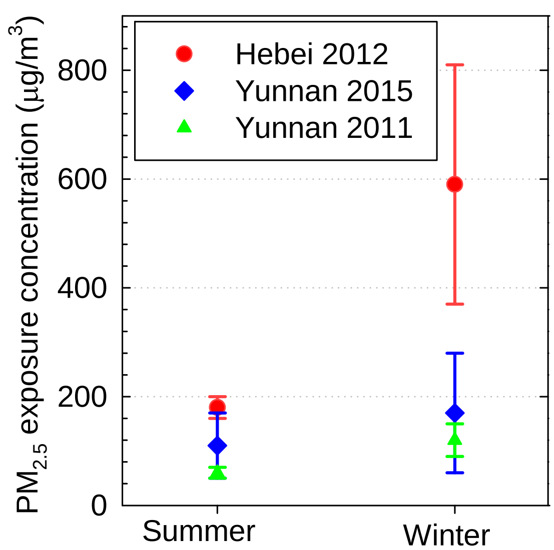


Fig. 13. Exposure concentrations of $PM_{2.5}$ in rural Hebei (in Northern China, winter heating region) and Yunnan provinces (in Southern China). People in the northern China are exposed to higher $PM_{2.5}$ concentrations than those who live in the southern China. Data was abtained from field studies (Baumgartner et al., 2011; Huang et al., 2015; Zhong et al., 2012).

Figures 12 shows that the exposure to fine PM among housewives is higher than that among the adult men, especially in winter, which is mainly due to housewives spending more time near the stove and inside the house. In addition, housewives from the rural northern China are exposed to 2 and 4 times higher $PM_{2.5}$ concentrations compared to those who live in the southern China during summer and winter, respectively.

In a brief summary, the factors affecting the personal inhalation exposure to fine PM are similar with those factor of affecting the indoor air quality, including the fuel/stove combination, household ventilation, and ambient air quality conditions. In addition, the time people spending in the house and near household stoves is another important factor. Thus the housewives have higher personal inhalation exposure level than the adult men. Children usually spend more time with their mother and also are likely to be exposed to higher indoor air pollution. The household solid fuel combustion leads to increased health risk via increasing the exposure to their emissions.

5. Determinants of emission factors

Flue gas from the household stove combustion is commonly and directly released to the atmosphere without any treatment by air pollution control device that has been widely installed for China's industrial boilers, such as for coal-fired power plants (Wang et al., 2014b; Wang and Hao, 2012; Wang et al., 2010b; Xu et al., 2009; Zhao et al., 2013). Pollutant EFs are mainly determined by two factors, i.e., the fuel quality and the combustion process, as briefly illustrated in Fig. 2. Parameters for the solid fuel quality mainly include contents of caloric value, moisture, volatile matter, ash, sulphur, chloride, toxic elements such as As, Hg, and Pb, as well as the fuel form such as briquette and pellet. No policy on biomass quality comes out in mainland China, while the government has introduced and updated policies on the residential coal quality to reduce pollutant emissions, e.g., increasing caloric value, lowering the threshold values for ash on dry basis (A_d, required to be less than 16% for Beijing-Tianjin-Hebei region), and volatile matter content on dry and ash-free basis (required to be less than 10% and 20% for anthracite and bituminous briquettes, respectively, in Beijing) (BMAQTS, 2013; NDRC, 2014).

The combustion process is mainly controlled by the stove technology and operational technique that depends on stove structure and resident skill level. The stove technology had been spontaneously developed until 1980s for at least 4000 years, the length of written China's history, as briefly illustrated in Fig. 1. China government has undertaken many programs to develop the household stove technology since the early 1980s (Qiu et al., 1996; Sinton et al., 2004; Smith et al., 1993b; Zhang et al., 2009b). China's Ministry of agriculture stated that about 85% rural households had improved biomass or coal cooking stoves in 2007 (CMA, 2008). Thermal efficiencies of these improved stoves should be not lower than 30%, while no fugitive emission from chimney is allowed (CMA, 2006). In fact, the current policy on residential solid fuels lacks of solid scientific supports from residential experiments.

Aiming to present the dominant determining factors on pollutant EFs, this section introduces the published results on fuel parameters and the stove technology. The fuel parameter mainly focuses on the fuel form, size, and contents of volatile matter content, ash, and sulphur. The stove technology mainly covers widely reported traditional stoves (see Fig. 1c) and recent developed advanced stoves in China.

5.1. Fuel quality

The solid fuel quality has been intensively investigated on its effect on pollutant EFs during household combustions. Coal's volatile matter content, one of the controlled coal parameters by Chinese government (BMAQTS, 2013; 2014), was found to be the dominant factor affecting EFs of PM, OC, and BC (Shen et al., 2010). Comparative investigation of chunk and briquette coal samples showed that honeycomb-coal briquette had about 40-80% lower EFs in various stoves (Chen et al., 2015b; Ge et al., 2004; Zhi et al., 2009). Significant variation of EF exists among different qualities of biomass. Biomass fuels made into pellets and briquettes were found to have much lower EFs than their raw (or unprocessed) materials (Johansson et al., 2004; Lim et al., 2012; Ravichandran and Corscadden, 2014; Shen et al., 2012). Figure 14 summarizes the reported $PM_{2.5}$ EFs from the residential solid fuel combustion. The $PM_{2.5}$ EFs fast increase with an increase in the fuel's volatile matter content till about 30% and then stay roughly flat for combustion in similar traditional household stoves. The $PM_{2.5}$ EFs of low volatile matter content fuel-- anthracite coal have been reported to an order of magnitude less than those of high volatile matter content fuels—bituminous/lignite coal and raw biomass (Chen et al., 2006; Li et al., 2016b; Li et al., 2016c; Shen et al., 2014). Measured $PM_{2.5}$ EFs for fuel samples with high volatile contents (lignite coals and biomass) often have large uncertainties, which are possibly related to unstable combustion during the coal ignition and pyrolysis stages.

Figure 15 shows the fractions of total carbonaceous species in $PM_{2.5}$ samples as a function of the fuel volatile matter content. Their trends are similar to the correlation between the $PM_{2.5}$ EF and the fuel volatile content (see Fig. 14). This indicates that the increase of the $PM_{2.5}$ EFs is driven by the incomplete combustions for high volatile content solid fuels, whose PMs contain high ratio of carbonaceous components. Because of the low burning efficiency in the household solid fuel combustion, generating more devolatilized matters (for higher volatile matter content fuel) in a short time period of pyrolysis stage leads to more unburned organic compounds which then serves as precursors (OC and EC) for the PM formation (Li et al., 2016b).

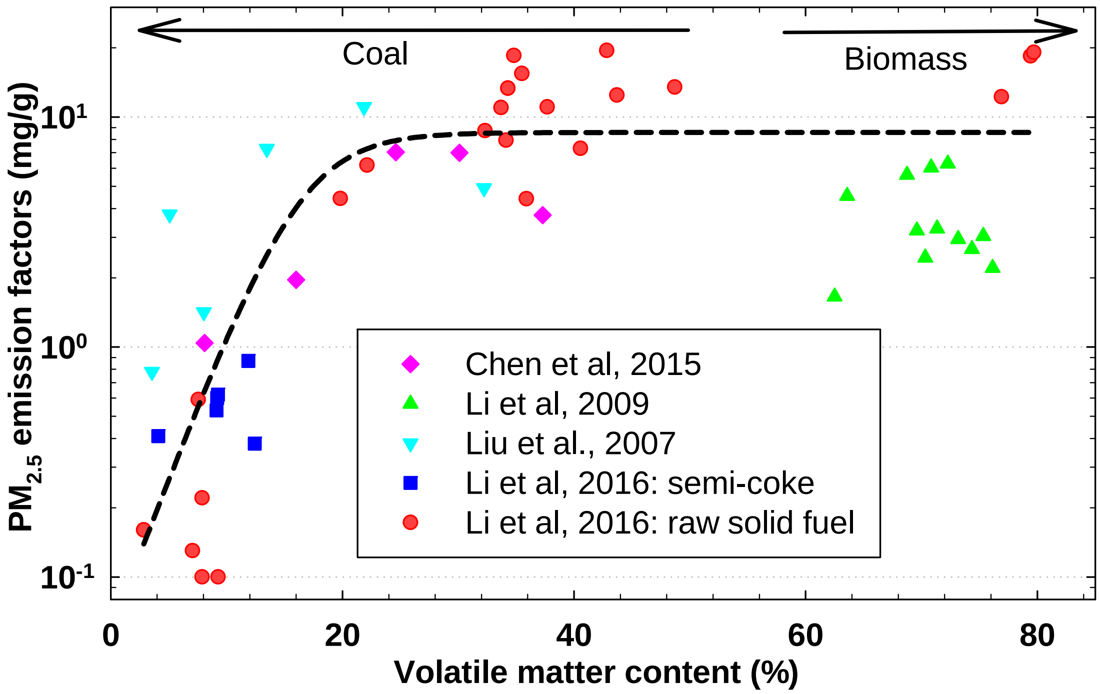


Fig. 14. $PM_{2.5}$ emission factors from residential coal and biomass combustions as a function of the fuel volatile matter content. Data was adapted from published literatures in various traditional household stoves and solid fuels in various forms (Chen et al., 2015b; Li et al., 2016a; Li et al., 2016b; Li et al., 2016c; Liu et al., 2007b). The dashed line roughly indicates the trend of $PM_{2.5}$ emission factor with the increase of the fuel volatile matter content.

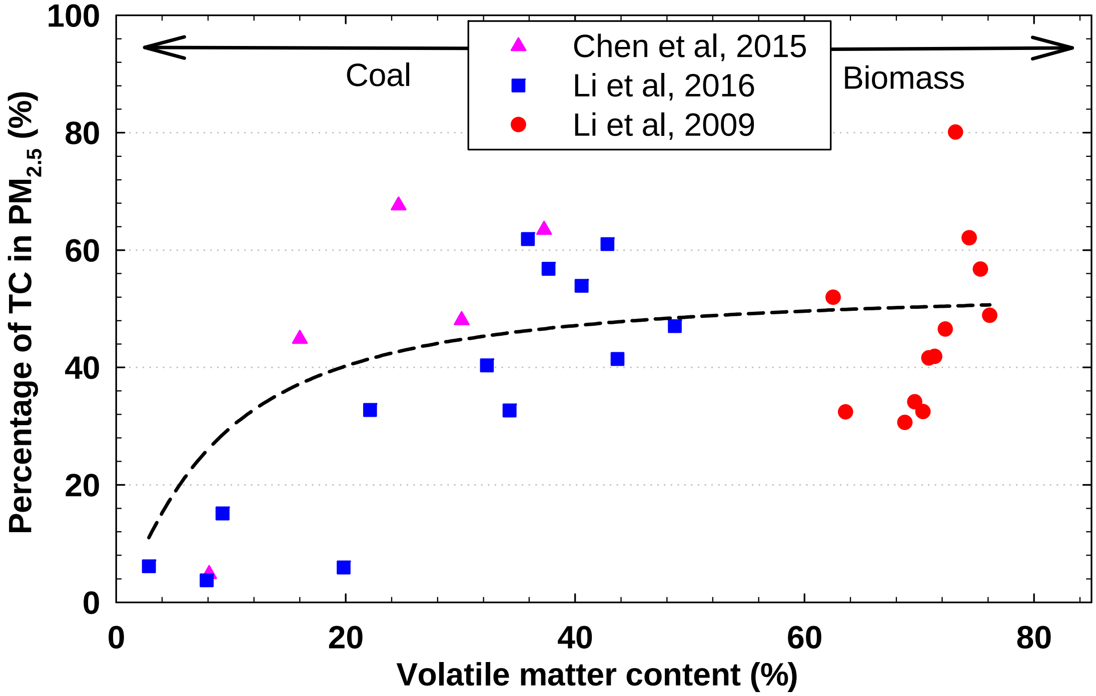


Fig. 15. The percentage of total carbonaceous component (TC = EC + OC) in $PM_{2.5}$ samples emitted from the residential solid fuel combustions as a function of the solid fuel volatile matter content. Data was adapted from published literatures (Chen et al., 2015b; Li et al., 2016b; Li et al., 2009). The dashed line roughly indicates the trend of TC ratio in $PM_{2.5}$ with the increase of the fuel volatile matter content.

The fuel form is another widely accepted method to control pollutant emissions. Making raw biomass (crop straws and wood) and coals into pellet and/or briquette forms were reported to have relatively low pollutant EFs (Bond et al., 2002; Chen et al., 2015b; Shen, 2015; Shen et al., 2012). However, particle-bound PAHs (the dominant form of PAHs in household flue gas) from coal briquettes were also reported to have significantly higher EFs than those from coal chunks (Chen et al., 2015c). The increase of clay content in the briquette was thought to serve as catalyst to crack down the coal tar into carbon and hydrogen, and thus reduce the emission of PM precursors (Bond et al., 2002; Landis et al., 1997). However, briquetting and pelleting technologies change fuel size and ash content simultaneously, while solid fuel size and ash content both was identified to affect PM emissions (Li et al., 2016b). Unfortunately, there are still no detailed report on the optimum form of solid fuels to reduce pollutant emission, including size, additive addition, molding pressure and humidity, and powder diameter ranges.

The fuel volatile matter content has been recognized to be the dominant factor among the reported solid fuel parameters on fuel quality. Beijing-Tianjin-Hebei governments have been making new policies to reduce pollutant emissions from the residential coal consumption by replacing low rank coal (high volatile matter content) with anthracite (low volatile matter content) with the help of financial subsidy since 2012. However, anthracite coal is not well accepted due to its difficulty in ignition and high price. Semi-coke briquette, made from bituminous and lignite coals by industrial carbonization treatment, was reported to be the clean solid fuel due to low volatile matte content (Li et al., 2016c). According to estimation, switching to semi-coke briquettes can reduce averaged EFs of $PM_{2.5}$, EC, and OC by about 93%, 98%, and 92%, respectively. Additionally, the semi-coke briquette has relatively lower price and higher burnout ratio in household stoves.

The replacement of raw coals with semi-coke briquettes was evaluated to be a feasible path to reduce pollution emissions. Figure 16 shows the hypothesized impact of this replacement on averaged $PM_{2.5}$ emission rates per household coal stoves at the provincial level in 2012, with referring to the WHO recommendation values (WHO, 2014). The replacement with semi-coke briquettes significantly reduces pollution emissions, especially in regions with high household coal consumption. The hypothesized analysis shows that the adoption of clean solid fuel can relieve the pollutant emissions from the household combustions in most rural China.

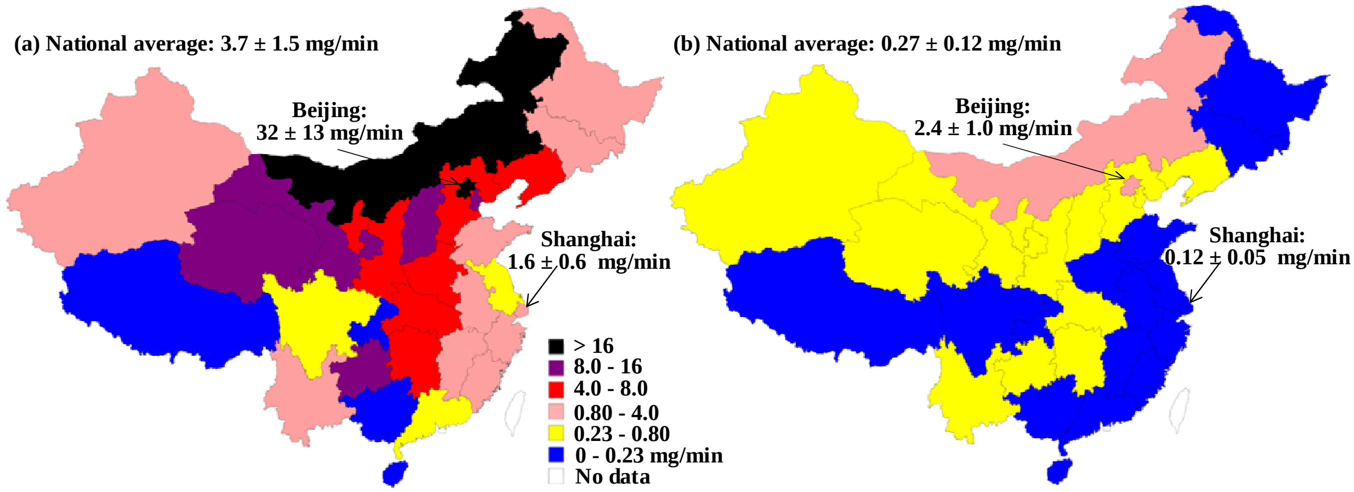


Fig. 16 Averaged $PM_{2.5}$ emission rates from household coal stoves at the provincial level for the year of 2012 in rural area of mainland China: (a) current raw coal consumption and (b) after the hypothetical replacement with semi-coke briquettes. The colours were marked with referring to the WHO recommendation values: 0.23 mg/min and 0.80 mg/min are for unvented and vented cases, respectively (WHO, 2014). These estimations of emission rate are with high uncertainties since there was no information for stove and coal distributions in China. Here we used the number of rural households as the stove number. Averaged amount of coal consumption in a household stove was obtained by diving the total consumed coal amount in rural with the total stove number in each province's rural. The averaged emission rate was then obtained by timing averaged coal amount per stove with emission factors, obtained from the experimental estimation (Li et al., 2016c).

5.2. Stove technology

Owing to the relatively inefficient stove technology associating with very incomplete combustion process, solid fuels burned in household stoves have much higher PM EFs than that in industrial boilers. Improved stoves with a high burning efficiency may have relatively low EFs and low fuel consumption (Edwards et al., 2007; Zhang et al., 2000). According to the estimation of reduction scenarios applied to a year-2010, cleaner stoves have the potential to provide better emission reduction when free fuels are used than the deployment of cleaner fuels (Winijkul and Bond, 2016).

The concept of “advance stove” has a different meaning at different periods. It mainly denoted the stove installed a chimney to remove emissions from indoor to outdoor without significant reduction of final emissions, and possessing a relatively higher energy efficiency than the three-stone stove before 1980s in mainland China (Smith et al., 1993a; Winijkul and Bond, 2016), see Fig. 1. However, the energy efficiency of these “advance stoves” for cooking was commonly lower than 10% (Sinton et al., 2004). After a continuous improvement since 1980s (Smith et al., 1993a), the thermal efficiency of cooking stoves for the household solid fuel combustion can be improved to be about 27% - 35% by changing the fuel burning form (Carter et al., 2014; Panwar and Rathore, 2008; Shen et al., 2015). Thus the current “advance stove” requires a higher thermal efficiency, such as about 30% and 70% for cooking stoves and heating stoves, respectively, as well as significant low pollutant EFs.

There are several reports on the evaluation of in-use emission and the thermal efficiency of updated biomass cooking stoves—gasifier cooking stove (Carter et al., 2014; Panwar and Rathore, 2008; Shen et al., 2015) and a new heating stove of employing under-fire combustion technology (Li et al., 2016d; Li et al., 2016e). The two advanced stoves were initially designed to reduce air pollution emissions from household biomass and coal combustions, respectively. Since the biomass has much higher volatile matter content than coal, there is no difficulty for carbonization and ignition in household stoves. The gasifier cooking stove increases the combustion efficiency of devolatilized organic matter by secondary air supply. However, the gasifier cooking stove is still no successful in burning coals, which can’t be carbonized and ignited easily in the small size household stoves (Shen et al., 2015). The under-fire technology, different from the over-fire technology commonly used in household stoves, separates the chamber space of solid fuel storage and combustion region. The solid fuels are carbonized and burned in the junction of the two regions, while the devolatilized organic matter was burned in the combustion region (Li et al., 2016e). The new heating stove was reported to improve the average thermal efficiency to be more than 80% for burning all tested fuel types (semi-coke, anthracite, briquette, bituminous, lignite, and biomass), as well as be effective in reducing CO_2 and pollutant emissions regardless of the volatile content in solid fuels. The average reductions of delivered energy-based EFs were ~87% for NH_3, 50% for CO_2, 79% for $PM_{2.5}$, 95% for EC, 85% for BaP–equivalent carcinogenic potency, and 66% for 8 selected toxic elements (Pb, Cu, Sb, Cd, As, Ag, Se, and Ni) in $PM_{2.5}$ (Li et al., 2016d; Li et al., 2016e). Improvement in household stove technologies has been demonstrated as a practical approach to improve the thermal efficiency and reduce the pollutant emissions and CO_2. However, further laboratory and field investigations on the combustion/thermal efficiency and pollutant emissions of updated combustion technologies are still needed. Furthermore, inventory of the stove changes are needed to be characterized quantitatively, since household heating and cooking stoves used in mainland China are changing very fast recently.

6. Summary

The current status of the indoor and ambient air pollution originating from the household coal and biomass combustion was reviewed in this study. The incomplete combustion of solid fuels in household stoves for cooking and heating activities has resulted in much higher pollutant EFs (such as PM, BC, PAH, and CO) than that of solid fuels combusted in industrial boilers, and thus caused seriously negative impacts on the air quality in China. Although annual pollutant emission has not increased significantly in the past decades due to the decreasing population of household solid fuel users (resulting from the urbanization rate and the economic development), the household relative contributions of CO, $PM_{2.5}$, BC, and PAH emissions have increased owing to increasingly strict pollutant control policy made to limit air pollution emissions from industrial boilers recently. Summarizing from various inventories, the household relative contributions of CO, $PM_{2.5}$, BC, and PAH emissions in all anthropogenic sources are more than 30%, 30%, 45%, and 60% in mainland China, respectively. Winter heating (northern China, such as Hebei) and less economically developed regions (southwest China, such as Guizhou and Sichuan) have suffered more negative impacts from the household solid fuel combustions than other regions (such as the richest region-Shanghai and Zhejiang). The geographical distribution of the indoor air quality has similar characteristics as that of impacts on the ambient air quality. Additionally, the household stoves without installing chimneys and poor household ventilation can lead to a poor indoor air quality especially when burning high volatile content solid fuels. Closely related with the ambient and indoor air quality, the personal inhalation exposure level in winter heating and less economically developed regions is higher than that in other regions. The time people spending near the cooking stoves is another important factor. The inhalation exposure level of various people in the rural area is generally in the order of adult men < children < housewives. Thus the household solid fuel combustion has led to an increased health risk, especially for household solid fuel users.

Pollutant EFs of the household solid fuel combustion rely on the fuel/stove combination. $PM_{2.5}$ and BC EFs have been identified to increase with the solid fuel volatile matter content in traditional household stoves. Advanced stoves, such as gasifier biomass cooking stoves for biomass and "under-fire" heating stoves for all solid fuels, can reduce pollutant emissions (including PM, BC, OC, PAH, CO, NH_3, and CO_2) by improving the combustion and thermal efficiencies. Thus the improvement of the combustion/thermal efficiencies of household stoves and the improvement of the solid fuel quality are the two essential methods to reduce pollutant emissions from households, as summarized in Fig. 17. Clean solid fuels, such as semi-coke briquette, and improved stoves have been both proposed to reduce PM emissions in China. However, cleaner solid fuels are typically more expensive, which in turn may result in residential consumers not choosing it. Thus a clean stove with low cost regardless of the fuel quality will be a good practical approach to reduce the air pollution in China.

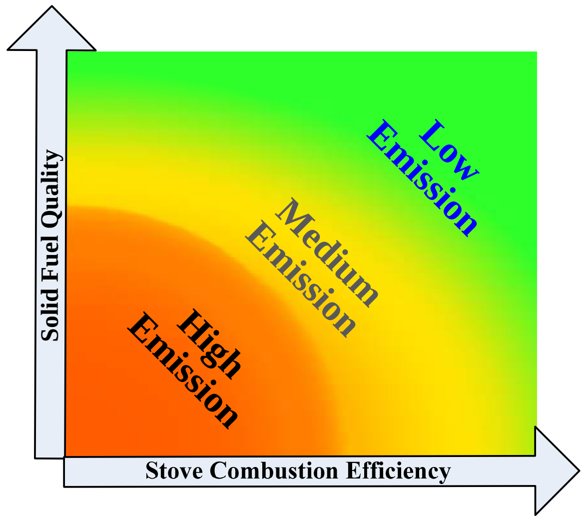


Fig. 17. Schematic diagram for the control of major pollutant emissions from household stoves. Solid fuel quality mainly includes the fuel volatile matter content, fuel size, and fuel form (Li et al., 2016b). Emission level mainly includes PM, BC/OC, and VOC, while some other pollutants such as SO_2 and NOx are not included.

Although the severe pollution situation, the resulting negative impacts from the household coal and biomass combustion, and reduction methods have been identified and emphasized, a systemic investigation of this problem and development of effective policies to significantly reduce pollutant emissions is still critically needed in China. There are large uncertainties in evaluating the air quality and health impacts resulted from the household combustion. Three major knowledge gaps are urgently needed to be filled. (1) Inventories for the temporal impact of the household solid fuel combustion on local ambient air. Since the solid fuel consumption strongly relies on season and local fuel availability. In addition, the population migration and the urbanization strongly affect the residential energy consumption. (2) Statistic data for the clean solid fuels and clean stove technologies, as well as the fuel/stove combination. As summarized in this review, the clean solid fuels and the advanced stoves can bring a significant reduction of air pollutant emissions. The deployment of the residential clean fuels and clean stoves used in mainland China changes very fast and depends on local government policy. There is no statistical data for the trend of these changes, but it is extremely important for estimating the indoor and ambient air quality in China. Thus the data should be better characterized in further studies. (3) The effect of socioeconomic development on the residential solid fuel consumption. It is well known that China's fast economic development and rapid urbanization have resulted in the per-capita consumption of energy and millions of rural-to-urban migrants, as well as the solid fuel and stove selections. However, there is still no quantitated estimation of this socioeconomic effect. Further investigation on this topic is needed to better understand the effect of China's socioeconomic development on residential pollutant emissions and associated health impacts.

In addition to filling these gaps, further research for practically reducing household pollution emissions is also urgently needed, especially on the topic of the high quality household stove and fuels with low cost for solving the problem in long-term. The clean stove should also be low pollutant emission when burning any solid fuel of containing any level of volatile matter. As a feasible approach to control household air pollution, costs of emission reduction by the clean stove and solid fuel should be considered with comparing to other clean energies, such as natural gas and electricity. The use of proper fuel/stove combinations will improve the air quality and benefit the human health. Furthermore, emission-abatement oriented policies should base on sound scientific evidence to reduce emissions, such as that improper contents in current residential coal standards should be corrected, the household stove standard should be updated soon, and potential policy alternatives beside subsidy for really clean fuels and stoves.

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References

Alnes LWH, Mestl HES, Berger J, Zhang HF, Wang SX, Dong ZQ, et al. Indoor PM and CO concentrations in rural Guizhou, China. Energy for Sustainable Development 2014; 21: 51-59.

Anenberg SC, Balakrishnan K, Jetter J, Masera O, Mehta S, Moss J, et al. Cleaner Cooking Solutions to Achieve Health, Climate, and Economic Cobenefits. Environmental Science & Technology 2013; 47: 3944-3952.

Armendariz-Arnez C, Edwards RD, Johnson M, Rosas IA, Espinosa F, Masera OR. Indoor particle size distributions in homes with open fires and improved Patsari cook stoves. Atmospheric Environment 2010; 44: 2881-2886.

Baumgartner J, Schauer JJ, Ezzati M, Lu L, Cheng C, Patz J, et al. Patterns and predictors of personal exposure to indoor air pollution from biomass combustion among women and children in rural China. Indoor Air 2011; 21: 479-488.

Blifford IH, Meeker GO. A Factor Analysis Model Of Large Scale Pollution. Atmospheric Environment 1967; 1: 147-157.

BMAQTS. Low sulfur content bulk coal and its products, DB//097-2013, Beijing: Beijing Municipal Administration of Quality and Technology Supervisio, BMAQTS, 2013 (In Chinese).

Bond TC, Covert DS, Kramlich JC, Larson TV, Charlson RJ. Primary particle emissions from residential coal burning: Optical properties and size distributions. Journal of Geophysical Research 2002; 107: 8347-8355.

Bond TC, Doherty SJ, Fahey DW, Forster PM, Berntsen T, DeAngelo BJ, et al. Bounding the role of black carbon in the climate system: A scientific assessment. Journal of Geophysical Research 2013; 118: 5380-5552.

Bond TC, Streets DG, Yarber KF, Nelson SM, Woo JH, Klimont Z. A technology-based global inventory of black and organic carbon emissions from combustion. Journal of Geophysical Research 2004; 109: D14203.

Brauer M, Amann M, Burnett RT, Cohen A, Dentener F, Ezzati M, et al. Exposure Assessment for Estimation of the Global Burden of Disease Attributable to Outdoor Air Pollution. Environmental Science & Technology 2012; 46: 652-660.

Brown KS, Marean CW, Herries AIR, Jacobs Z, Tribolo C, Braun D, et al. Fire As an Engineering Tool of Early Modern Humans. Science 2009; 325: 859-862.

Bruce N, Perez-Padilla R, Albalak R. Indoor air pollution in developing countries: a major environmental and public health challenge. Bulletin of the World Health Organization 2000; 78: 1078-1092.

Cao JJ, Wu F, Chow JC, Lee SC, Li Y, Chen SW, et al. Characterization and source apportionment of atmospheric organic and elemental carbon during fall and winter of 2003 in Xi'an, China. Atmospheric Chemistry and Physics 2005; 5: 3127-3137.

Carter EM, Shan M, Yang XD, Li JR, Baumgartner J. Pollutant Emissions and Energy Efficiency of Chinese Gasifier Cooking Stoves and Implications for Future Intervention Studies. Environmental Science & Technology 2014; 48: 6461-6467.

Chafe ZA, Brauer M, Klimont Z, Van Dingenen R, Mehta S, Rao S, et al. Household Cooking with Solid Fuels Contributes to Ambient PM2.5 Air Pollution and the Burden of Disease. Environmental Health Perspectives 2014; 122: 1314-1320.

Chen Y, Shen G, Huang Y, Zhang Y, Han Y, Wang R, et al. Household air pollution and personal exposure risk of polycyclic aromatic hydrocarbons among rural residents in Shanxi, China. Indoor Air 2015a: 94-99.

Chen Y, Tian C, Feng Y, Zhi G, Li J, Zhang G. Measurements of emission factors of PM2.5, OC, EC, and BC for household stoves of coal combustion in China. Atmospheric Environment 2015b; 109: 190-196.

Chen YJ, Zhi GR, Feng YL, Fu JM, Feng JL, Sheng GY, et al. Measurements of emission factors for primary carbonaceous particles from residential raw-coal combustion in China. Geophysical Research Letters 2006; 33: L20815-L20818.

Chen YJ, Zhi GR, Feng YL, Liu DY, Zhang G, Li J, et al. Measurements of Black and Organic Carbon Emission Factors for Household Coal Combustion in China: Implication for Emission Reduction. Environmental Science & Technology 2009; 43: 9495-9500.

Chen YJ, Zhi GR, Feng YL, Tian CG, Bi XH, Li J, et al. Increase in polycyclic aromatic hydrocarbon (PAH) emissions due to briquetting: A challenge to the coal briquetting policy. Environ Poll 2015c; 204: 58-63.

CMA. Agricultural industry standard of the people's Republic of China. Technical specification of domestic improved stoves and kangs for firewood and coal (NY/T 1001-2006). Ministry of Agriculture of the People's Republic of China, 2006 (In Chinese).

CMA. Editor of the China Rural Energy Yearbook, China Rural Energy Yearbook 2000-2008. Beijing: Chinese Agricultural Press, 2008 (In Chinese).

Dai SF, Ren DY, Chou CL, Finkelman RB, Seredin VV, Zhou YP. Geochemistry of trace elements in Chinese coals: A review of abundances, genetic types, impacts on human health, and industrial utilization. International Journal of Coal Geology 2012; 94: 3-21.

Ding JN, Zhong JJ, Yang YF, Li BG, Shen GF, Su YH, et al. Occurrence and exposure to polycyclic aromatic hydrocarbons and their derivatives in a rural Chinese home through biomass fuelled cooking. Environmental Pollution 2012; 169: 160-166.

Downward GS, Hu W, Rothman N, Reiss B, Wu GP, Wei FS, et al. Polycyclic Aromatic Hydrocarbon Exposure in Household Air Pollution from Solid Fuel Combustion among the Female Population of Xuanwei and Fuyuan Counties, China. Environmental Science & Technology 2014; 48: 14632-14641.

Duan XL, Jiang Y, Wang BB, Zhao XG, Shen GF, Cao SZ, et al. Household fuel use for cooking and heating in China: Results from the first Chinese Environmental Exposure-Related Human Activity Patterns Survey (CEERHAPS). Applied Energy 2014; 136: 692-703.

Edwards RD, Li Y, He G, Yin Z, Sinton J, Peabody J, et al. Household CO and PM measured as part of a review of China's National Improved Stove Program. Indoor Air 2007; 17: 189-203.

Fischer SL, Koshland CP. Daily and peak 1 h indoor air pollution and driving factors in a rural Chinese village. Environmental Science & Technology 2007; 41: 3121-3126.

Gao X, Yu Q, Gu Q, Chen Y, Ding K, Zhu J, et al. Indoor air pollution from solid biomass fuels combustion in rural agricultural area of Tibet, China. Indoor Air 2009; 19: 198-205.

Gaspari L, Chang SS, Santella RM, Garte S, Pedotti P, Taioli E. Polycyclic aromatic hydrocarbon DNA adducts in human sperm as a marker of DNA damage and infertility. Mutation Research-Genetic Toxicology and Environmental Mutagenesis 2003; 535: 155-160.

GBD2010. Ambient Air Pollution Risk Model 1990 - 2010. Seattle, United States: Institute for Health Metrics and Evaluation (IHME), 2013.

Ge S, Xu X, Chow JC, Watson J, Sheng Q, Liu WL, et al. Emissions of air pollutants from household stoves: Honeycomb coal versus coal cake. Environmental Science & Technology 2004; 38: 4612-4618.

Guo S, Hu M, Zamora ML, Peng JF, Shang DJ, Zheng J, et al. Elucidating severe urban haze formation in China. Proceedings of the National Academy of Sciences of the United States of America 2014; 111: 17373-17378.

He GL, Ying B, Liu J, Gao SR, Shen S, Balakrishnan K, et al. Patterns of household concentrations of multiple indoor air pollutants in China. Environmental Science & Technology 2005; 39: 991-998.

Henry RC, Christensen ER. Selecting an Appropriate Multivariate Source Apportionment Model Result. Environmental Science & Technology 2010; 44: 2474-2481.

Hu NJ, Shi XF, Liu JH, Huang P, Liu YG, Liu Y. Concentrations and possible sources of PAHs in sediments from Bohai Bay and adjacent shelf. Environmental Earth Sciences 2010; 60: 1771-1782.

Hu W, Downward GS, Reiss B, Xu J, Bassig BA, Hosgood HD, et al. Personal and Indoor PM2.5 Exposure from Burning Solid Fuels in Vented and Unvented Stoves in a Rural Region of China with a High Incidence of Lung Cancer. Environmental Science & Technology 2014; 48: 8456-8464.

Huang RJ, Zhang YL, Bozzetti C, Ho KF, Cao JJ, Han YM, et al. High secondary aerosol contribution to particulate pollution during haze events in China. Nature 2014a; 514: 218-222.

Huang Y, Shen HZ, Chen H, Wang R, Zhang YY, Su S, et al. Quantification of Global Primary Emissions of PM2.5, PM10, and TSP from Combustion and Industrial Process Sources. Environmental Science & Technology 2014b; 48: 13834-13843.

Huang W, Baumgartner J, Zhang YX, Wang YQ, Schauer JJ. Source apportionment of air pollution exposures of rural Chinese women cooking with biomass fuels. Atmospheric Environment 2014c; 104: 79-87.

IPCC. Climate change 2013 : the physical science basis : Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change: Cambridge University Press, 2014.

James SR. Hominid Use of Fire In the Lower And Middle Pleistocene - a Review of the Evidence. Current Anthropology 1989; 30: 1-26.

Jin Y, Ma X, Chen X, Cheng Y, Baris E, Ezzati M, et al. Exposure to indoor air pollution from household energy use in rural China: The interactions of technology, behavior, and knowledge in health risk management. Social Science & Medicine 2006; 62: 3161-3176.

Jin YL, Zhou Z, He GL, Wei HZ, Liu J, Liu F, et al. Geographical, spatial, and temporal distributions of multiple indoor air pollutants in four Chinese provinces. Environmental Science & Technology 2005; 39: 9431-9439.

Johansson LS, Leckner B, Gustavsson L, Cooper D, Tullin C, Potter A. Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. Atmospheric Environment 2004; 38: 4183-4195.

Kang YN, Liu MX, Song Y, Huang X, Yao H, Cai XH, et al. High-resolution ammonia emissions inventories in China from 1980 to 2012. Atmospheric Chemistry And Physics 2016; 16: 2043-2058.

Kim C, Gao YT, Xiang YB, Barone-Adesi F, Zhang YW, Hosgood HD, et al. Home kitchen ventilation, cooking fuels, and lung cancer risk in a prospective cohort of never smoking women in Shanghai, China. International Journal Of Cancer 2015a; 136: 632-638.

Kim KH, Kabir E, Kabir S. A review on the human health impact of airborne particulate matter. Environment International 2015b; 74: 136-143.

Landis ER, Bostick NH, Gluskoter HJ, Harrison CD, Huber DW, Johnson EA. Assessment of the coal resources of the Kyrgyz Republic; coal character and distribution, geology, mining, and importance to the nation's future. U.S. Geological Survey : Branch of Information Services, 1997.

Lang YH, Yang X, Wang H, Yang W, Li GL. Diagnostic Ratios and Positive Matrix Factorization to Identify Potential Sources of PAHS in Sediments of the Rizhao Offshore, China. Polycyclic Aromatic Compounds 2013; 33: 161-172.

Lei Y, Zhang Q, He KB, Streets DG. Primary anthropogenic aerosol emission trends for China, 1990-2005. Atmospheric Chemistry and Physics 2011; 11: 931-954.

Li AG, Jones PJ. Developments in strategies used for natural and mechanical ventilation in China. Indoor And Built Environment 2000; 9: 65-74.

Li Q, Duan L, Jiang J, Wang S, Hao J. Investigation of Reducing Potential for Primary Particulate Emission from Residential Coal Combustion in China. Chin Soc for Elec Eng 2016a; 36: 4408-14.

Li Q, Jiang J, Zhang Q, Zhou W, Cai S, Duan L, et al. Influences of coal size, volatile matter content, and additive on primary particulate matter emissions from household stove combustion. Fuel 2016b; 182: 780-787.

Li Q, Li XH, Jiang JK, Duan L, Ge S, Zhang Q, et al. Semi-coke briquettes: towards reducing emissions of primary PM2.5, particulate carbon, and carbon monoxide from household coal combustion in China. Scientific Reports 2016c; 6: 19306-19311.

Li, Q., Jiang, J., Cai, S., Zhou, W., Wang, S., Duan, L., et al. Gaseous Ammonia Emissions from Coal and Biomass Combustion in Household Stoves with Different Combustion Efficiencies. Environmental Science & Technology Letters, 2016d; 3: 98-103.

Li, Q., Jiang, J., Qi, J., Deng, J., Yang, D., Wu, J., , et al. Improving the Energy Efficiency of Stoves to Reduce Pollutant Emissions from Household Solid Fuel Combustion in China. Environmental Science & Technology Letters, 2016e; DOI: 10.1021/acs.estlett.6b00324.

Li XH, Duan L, Wang SX, Duan JC, Guo XM, Yi HH, et al. Emission characteristics of particulate matter from rural household biofuel combustion in China. Energy & Fuels 2007; 21: 845-851.

Li XH, Wang SX, Duan L, Hao JM, Nie YF. Carbonaceous Aerosol Emissions from Household Biofuel Combustion in China. Environmental Science & Technology 2009; 43: 6076-6081.

Liao CP, Wu CZ, Yanyongjie, Huang HT. Chemical elemental characteristics of biomass fuels in China. Biomass & Bioenergy 2004; 27: 119-130.

Lim SS, Vos T, Flaxman AD. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010 (vol 380, pg 2224, 2012). Lancet 2013; 381: 1276-1276.

Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 2012; 380: 2224-2260.

Liu SZ, Tao S, Liu WX, Liu YN, Dou H, Zhao JY, et al. Atmospheric polycyclic aromatic hydrocarbons in north China: A winter-time study. Environmental Science & Technology 2007a; 41: 8256-8261.

Liu Y, Zhang YX, Wei YJ, Dou H, Gu DS, Zeng LM, et al. Measurement of emission factors of carbonaceous aerosols from residential coal combustion. Acta Science Circumstantiae 2007b; 27: 1409-1416 (In Chinese).

Lu Z, Zhang Q, Streets DG. Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996-2010. Atmospheric Chemistry and Physics 2011; 11: 9839-9864.

Ma L, Dong Z, Wu K, Pan J. Indoor Air Quality and Characteristics of Fine Particle for Rural Guizhou. J Environmental Monitoring in China 2015; 1: 28-34 (in Chinese).

Matson NE, Sherman MH. Why we ventilate our houses-An historical look. Lawrence Berkeley National Laboratory 2004.

Mestl HES, Aunan K, Seip HM, Wang S, Zhao Y, Zhang D. Urban and rural exposure to indoor air pollution from domestic biomass and coal burning across China. Science of the Total Environment 2007; 377: 12-26.

Mumford JL, He XZ, Chapman RS, Cao SR, Harris DB, Li XM, et al. Lung-Cancer And Indoor Air-Pollution In Xuan-Wei, China. Science 1987; 235: 217-220.

NBSC. National Bureau of Statistics of China (NBSC), China Energy Statistical Yearbook (2008). China Stat. Press, Beijing, 2008 (In Chinese).

NBSC. China Energy Statistical Yearbook (2014), National Bureau of Statistics of China (in Chinese). China Statistics Press, Beijing, China, 2015 (In Chinese).

NDRC. Interim Measures for the Administration of Commercial Coal Quality. NDRC, China: National Development and Reform Commission, NDRC, 2014 (In Chinese).

Ohara T, Akimoto H, Kurokawa J, Horii N, Yamaji K, Yan X, et al. An Asian emission inventory of anthropogenic emission sources for the period 1980-2020. Atmospheric Chemistry and Physics 2007; 7: 4419-4444.

Okuda T, Okamoto K, Tanaka S, Shen ZX, Han YM, Huo ZQ. Measurement and source identification of polycyclic aromatic hydrocarbons (PAHs) in the aerosol in Xi'an, China, by using automated column chromatography and applying positive matrix factorization (PMF). Science of the Total Environment 2010; 408: 1909-1914.

Panwar NL, Rathore NS. Design and performance evaluation of a 5 kW producer gas stove. Biomass & Bioenergy 2008; 32: 1349-1352.

Peabody JW, Riddell TJ, Smith KR, Liu YP, Zhao YY, Gong JH, et al. Indoor air pollution in rural China: Cooking fuels, stoves, and health status. Archives of Environmental & Occupational Health 2005; 60: 86-95.

Perez-Padilla R, Schilmann A, Riojas-Rodriguez H. Respiratory health effects of indoor air pollution. International Journal Of Tuberculosis And Lung Disease 2010; 14: 1079-1086.

Qiu DX, Gu SH, Catania P, Huang K. Diffusion of improved biomass stoves in China. Energy Policy 1996; 24: 463-469.

Ravichandran P, Corscadden K. Comparison of gaseous and particle emissions produced from leached and un-leached agricultural biomass briquettes. Fuel Processing Technology 2014; 128: 359-366.

Roebroeks W, Villa P. On the earliest evidence for habitual use of fire in Europe. Proceedings Of the National Academy Of Sciences Of the United States Of America 2011; 108: 5209-5214.

Ru MY, Tao S, Smith K, Shen GF, Shen HZ, Huang Y, et al. Direct Energy Consumption Associated Emissions by Rural-to-Urban Migrants in Beijing. Environmental Science & Technology 2015; 49: 13708-13715.

Shao LY, Hu Y, Wang J, Hou C, Yang YY, Wu MY. Particle-induced oxidative damage of indoor PM10 from coal burning homes in the lung cancer area of Xuan Wei, China. Atmospheric Environment 2013; 77: 959-967.

Shen G, Xue M, Chen Y, Yang C, Li W, Shen H, et al. Comparison of carbonaceous particulate matter emission factors among different solid fuels burned in residential stoves. Atmospheric Environment 2014; 89: 337-345.

Shen GF. Quantification of emission reduction potentials of primary air pollutants from residential solid fuel combustion by adopting cleaner fuels in China. Journal of Environmental Sciences 2015; 37: 1-7.

Shen GF, Chen YC, Xue CY, Lin N, Huang Y, Shen HZ, et al. Pollutant Emissions from Improved Coal- and Wood-Fuelled Cookstoves in Rural Households. Environmental Science & Technology 2015; 49: 6590-6598.

Shen GF, Tao S, Wei SY, Chen YC, Zhang YY, Shen HZ, et al. Field Measurement of Emission Factors of PM, EC, OC, Parent, Nitro-, and Oxy- Polycyclic Aromatic Hydrocarbons for Residential Briquette, Coal Cake, and Wood in Rural Shanxi, China. Environmental Science & Technology 2013a; 47: 2998-3005.

Shen GF, Tao S, Wei SY, Zhang YY, Wang R, Wang B, et al. Reductions in Emissions of Carbonaceous Particulate Matter and Polycyclic Aromatic Hydrocarbons from Combustion of Biomass Pellets in Comparison with Raw Fuel Burning. Environmental Science & Technology 2012; 46: 6409-6416.

Shen GF, Yang YF, Wang W, Tao S, Zhu C, Min YJ, et al. Emission Factors of Particulate Matter and Elemental Carbon for Crop Residues and Coals Burned in Typical Household Stoves in China. Environmental Science & Technology 2010; 44: 7157-7162.

Shen HZ, Huang Y, Wang R, Zhu D, Li W, Shen GF, et al. Global Atmospheric Emissions of Polycyclic Aromatic Hydrocarbons from 1960 to 2008 and Future Predictions. Environmental Science & Technology 2013b; 47: 6415-6424.

Sinton JE, Smith KR, Peabody JW, Yaping L, Xiliang Z, Edwards R, et al. An assessment of programs to promote improved household stoves in China. Energy for Sustainable Development 2004; 8: 33-52.

Smith KR, Balakrishnan K, Butler C, Chafe Z, Fairlie I, Kinney P, et al. Chapter 4 - Energy and Health. Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012, pp. 255-324.

Smith KR, Gu SH, Huang K, Qiu DX. 100-Million Improved Cookstoves In China - How Was It Done. World Development 1993a; 21: 941-961.

Smith KR, Jerrett M, Anderson HR, Burnett RT, Stone V, Derwent R, et al. Health and Climate Change 5 Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants. Lancet 2009; 374: 2091-2103.

Smith KR, Mehta S, Maeusezahl-Feuz M. Indoor air pollution from household use of solid fuels. Comparative quantification of health risks: global and regional burden of disease attributable to selected major risk factors 2004; 2: 1435-93.

Smith KR, Shuhua G, Kun H, Daxiong Q. One hundred million improved cookstoves in China: How was it done? World Development 1993b; 21: 941-961.

Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, et al. Climate change 2013: The physical science basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5)(Cambridge Univ Press, New York) 2013.

Streets DG, Bond TC, Carmichael GR, Fernandes SD, Fu Q, He D, et al. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. Journal of Geophysical Research-Atmospheres 2003; 108.

Tian FL, Chen JW, Qiao XL, Wang Z, Yang P, Wang DG, et al. Sources and seasonal variation of atmospheric polycyclic aromatic hydrocarbons in Dalian, China: Factor analysis with non-negative constraints combined with local source fingerprints. Atmospheric Environment 2009; 43: 2747-2753.

Wang DG, Tian FL, Yang M, Liu CL, Li YF. Application of positive matrix factorization to identify potential sources of PAHs in soil of Dalian, China. Environmental Pollution 2009a; 157: 1559-1564.

Wang DX, Hu JL, Xu Y, Lv D, Xie XY, Kleeman M, et al. Source contributions to primary and secondary inorganic particulate matter during a severe wintertime PM2.5 pollution episode in Xi'an, China. Atmospheric Environment 2014a; 97: 182-194.

Wang J, Wang Z, Zhao B, Wang S, Hao J. Cost-Effectiveness Analysis of Multi-Pollutant Emission Reduction in Power Sector of China. Research of Environmental Sciences 2014b; 27: 1314-1322 (in Chinese).

Wang Q, Shao M, Zhang Y, Wei Y, Hu M, Guo S. Source apportionment of fine organic aerosols in Beijing. Atmospheric Chemistry and Physics 2009b; 9: 8573-8585.

Wang R, Tao S, Shen HZ, Huang Y, Chen H, Balkanski Y, et al. Trend in Global Black Carbon Emissions from 1960 to 2007. Environmental Science & Technology 2014c; 48: 6780-6787.

Wang R, Tao S, Wang WT, Liu JF, Shen HZ, Shen GF, et al. Black Carbon Emissions in China from 1949 to 2050. Environmental Science & Technology 2012; 46: 7595-7603.

Wang SX, Hao JM. Air quality management in China: Issues, challenges, and options. Journal of Environmental Sciences-China 2012; 24: 2-13.

Wang SX, Wei W, Li D, Aunan K, Hao JM. Air pollutants in rural homes in Guizhou, China - Concentrations, speciation, and size distribution. Atmospheric Environment 2010a; 44: 4575-4581.

Wang SX, Zhang L, Li GH, Wu Y, Hao JM, Pirrone N, et al. Mercury emission and speciation of coal-fired power plants in China. Atmospheric Chemistry and Physics 2010b; 10: 1183-1192.

Wang SX, Zhao B, Cai SY, Klimont Z, Nielsen CP, Morikawa T, et al. Emission trends and mitigation options for air pollutants in East Asia. Atmospheric Chemistry and Physics 2014d; 14: 6571-6603.

Wang Y, Zhang RY, Saravanan R. Asian pollution climatically modulates mid-latitude cyclones following hierarchical modelling and observational analysis. Nature Communications 2014e; 5: 3098-3102.

Wang Y, Zhuang GS, Tang AH, Yuan H, Sun YL, Chen SA, et al. The ion chemistry and the source of PM2.5 aerosol in Beijing. Atmospheric Environment 2005; 39: 3771-3784.

Wang YJ, Li L, Chen CH, Huang C, Huang HY, Feng JL, et al. Source apportionment of fine particulate matter during autumn haze episodes in Shanghai, China. Journal of Geophysical Research-Atmospheres 2014f; 119: 1903-1914.

Wei S, Su Y, Shen G, Tao S, Min Y, Wei W. Emission factors of particulate matter and elemental carbon from rural residential wood combustion. Asian Journal of Ecotoxicology 2013; 8: 29-35 (in Chinese).

Wei SY, Shen GF, Zhang YY, Xue M, Xie H, Lin PC, et al. Field measurement on the emissions of PM, OC, EC and PAHs from indoor crop straw burning in rural China. Environmental Pollution 2014; 184: 18-24.

WHO. WHO Indoor Air Quality Guidelines: Household Fuel Combustion, Geneva, 2014.

Winijkul E, Bond TC. Emissions from residential combustion considering end-uses and spatial constraints: Part II, emission reduction scenarios. Atmospheric Environment 2016; 124: 1-11.

Wu FY, Liu XP, Wang W, Man YB, Chan CY, Liu WX, et al. Characterization of particulate-bound PAHs in rural households using different types of domestic energy in Henan Province, China. Science Of the Total Environment 2015a; 536: 840-846.

Wu FY, Wang W, Man YB, Chan CY, Liu WX, Tao S, et al. Levels of PM2.5/PM10 and associated metal(loid)s in rural households of Henan Province, China. Science of the Total Environment 2015b; 512: 194-200.

Xia Y, Zhao Y, Nielsen CP. Benefits of China's efforts in gaseous pollutant control indicated by the bottom-up emissions and satellite observations 2000–2014. Atmospheric Environment 2016; 136: 43-53.

Xu SS, Liu WX, Tao S. Emission of polycyclic aromatic hydrocarbons in China. Environmental Science & Technology 2006; 40: 702-708.

Xu Y, Williams RH, Socolow RH. China's rapid deployment of SO2 scrubbers. Energy & Environmental Science 2009; 2: 459-465.

Zhang HF, Wang SX, Hao JM, Wan L, Jiang JK, Zhang M, et al. Chemical and size characterization of particles emitted from the burning of coal and wood in rural households in Guizhou, China. Atmospheric Environment 2012a; 51: 94-99.

Zhang HF, Zhu T, Wang SX, Hao JM, Mestl HES, Alnes LWH, et al. Indoor Emissions of Carbonaceous Aerosol and Other Air Pollutants from Household Fuel Burning in Southwest China. Aerosol and Air Quality Research 2014a; 14: 1779-1788.

Zhang J, Smith KR, Ma Y, Ye S, Jiang F, Qi W, et al. Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors. Atmospheric Environment 2000; 34: 4537-4549.

Zhang Q, Streets DG, Carmichael GR, He KB, Huo H, Kannari A, et al. Asian emissions in 2006 for the NASA INTEX-B mission. Atmospheric Chemistry and Physics 2009a; 9: 5131-5153.

Zhang Q, Streets DG, He KB, Klimont Z. Major components of China's anthropogenic primary particulate emissions. Environmental Research Letters 2007; 2: 045027-045033.

Zhang W, Chen X, Liu X, Liu G. Development of biomass stoves and their application in China. Chemical Industy and Engineering Progress 2009b; 28: 516-520 (In Chinese).

Zhang W, Tong YD, Wang HH, Chen L, Ou LB, Wang XJ, et al. Emission of Metals from Pelletized and Uncompressed Biomass Fuels Combustion in Rural Household Stoves in China. Scientific Reports 2014b; 4: 5611-5616.

Zhang Y, Guo CS, Xu J, Tian YZ, Shi GL, Feng YC. Potential source contributions and risk assessment of PAHs in sediments from Taihu Lake, China: Comparison of three receptor models. Water Research 2012b; 46: 3065-3073.

Zhang YJ, Zheng M, Cai J, Yan CQ, Russell AG, Wang XS, et al. Comparison and overview of PM2.5 source apportionment methods. Chinese Science Bulletin 2015; 60: 109-121 (in Chinese).
Zhang YX, Schauer JJ, Zhang YH, Zeng LM, Wei YJ, Liu Y, et al. Characteristics of particulate carbon emissions from real-world Chinese coal combustion. Environmental Science & Technology 2008; 42: 5068-5073.
Zhang YX, Tao S. Global atmospheric emission inventory of polycyclic aromatic hydrocarbons (PAHs) for 2004. Atmospheric Environment 2009; 43: 812-819.
Zhao B, Wang SX, Liu H, Xu JY, Fu K, Klimont Z, et al. NOx emissions in China: historical trends and future perspectives. Atmospheric Chemistry and Physics 2013; 13: 9869-9897.
Zhao B, Wang SX, Xing J, Fu K, Fu JS, Jang C, et al. Assessing the nonlinear response of fine particles to precursor emissions: development and application of an extended response surface modeling technique v1.0. Geosci. Model Dev. 2015; 8: 115-128.
Zhao Y, Nielsen CP, Lei Y, McElroy MB, Hao J. Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China. Atmospheric Chemistry and Physics 2011; 11: 2295-2308.
Zhi GR, Peng CH, Chen YJ, Liu DY, Sheng GY, Fu JM. Deployment of Coal Briquettes and Improved Stoves: Possibly an Option for both Environment and Climate. Environmental Science & Technology 2009; 43: 5586-5591.
Zhong J. Primary Studies on Particulate Matter and PAHs Pollution in the Rural Indoor Air and Their Human Exposure. Master. Xinjiang University, 2011 (in Chinese).
Zhong JJ, Ding JN, Su YH, Shen GF, Yang YF, Wang C, et al. Carbonaceous Particulate Matter Air Pollution and Human Exposure from Indoor Biomass Burning Practices. Environmental Engineering Science 2012; 29: 1038-1045.