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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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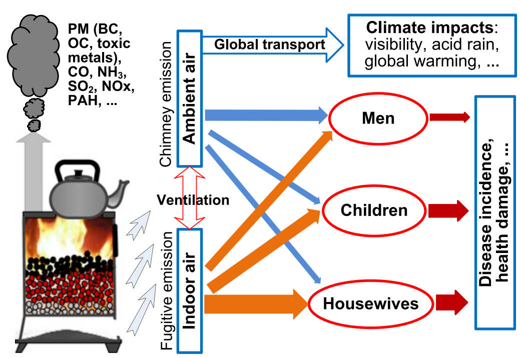
HIGHLIGHTS

- 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.

GRAPHICAL ABSTRACT



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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 regions, such as Guizhou (61% $PM_{2.5}$, 80% BC), than that in more developed regions, 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 pollutant emissions. $PM_{2.5}$ and BC emission factors (EFs) have been identified to increase with volatile matter content 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 volatile matter content in solid fuel. However, there are still some knowledge gaps, such as, inventory for the temporal impact of household combustion on air quality, statistic data for deployed clean solid fuels and advanced stoves, and the effect of

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socioeconomic development. Additionally, further technology research for reducing air pollution emissions is urgently needed, especially low cost and clean stove when burning any type of solid fuel. Furthermore, emission-abatement oriented policy should base on sound scientific evidence to significantly reduce pollutant emissions.

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 BCE (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 CE. Fig. 1 shows a brief illustration of the developments related to household solid fuel combustion.

Why pollutant species are released during household solid fuel combustion? Ideally, complete combustion of fuels only 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 commonly 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, sulphur 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.

Why the indoor air pollution related to 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). Fig. 3(b) and (c) suggests that coal and biomass are still widely used as residential solid fuels in mainland China. Residential coal has

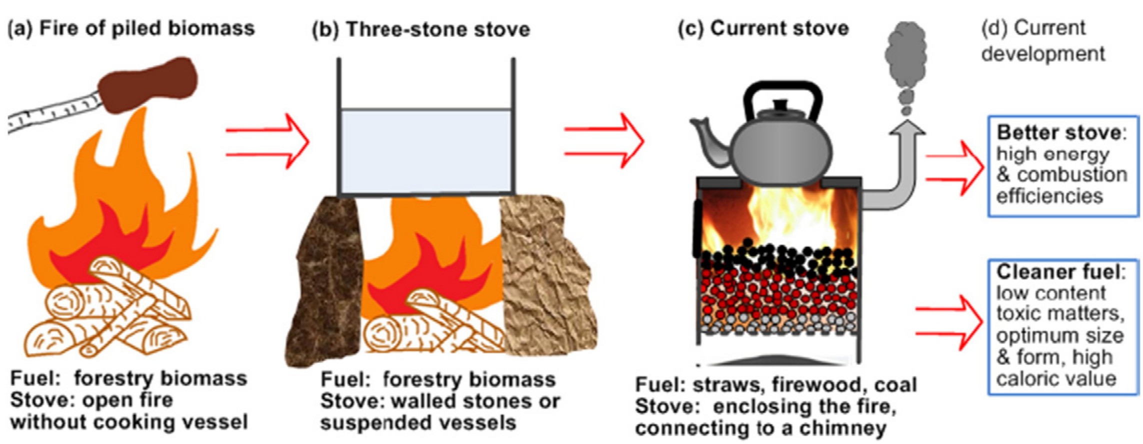

Fig. 1. Brief illustration of the development for household solid fuel combustion from the hominid time to the current status.