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Air pollutant emissions and mitigation potential through the adoption of semi-coke coals and improved heating stoves: Field evaluation of a pilot intervention program in rural China☆

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ABSTRACT

Pollutant emissions from incomplete combustion of raw coal in low-efficiency residential heating stoves greatly contribute to winter haze in China. Semi-coke coals and improved heating stoves are expected to lower air pollutant emissions and are vigorously promoted by the Chinese government in many national and local plans. In this study, the thermal performance and air pollutant emissions from semi-coke combustion in improved heating stoves were measured in a pilot rural county and compared to the baseline of burning raw coal to quantify the mitigation potential of air pollutant emissions. A total of five stove-fuel combinations were tested, and 27 samples from 27 different volunteered households were obtained. The heating efficiency of improved stoves increased, but fuel consumption appeared higher with more useful energy output compared to traditional stoves. The emission factors of $PM_{2.5}$, SO_2, and CO_2 of semi-coke burning in specified improved stoves were lower than the baseline of burning raw coal chunk, but no significant NOx and CO decreases were observed. The total amount of $PM_{2.5}$ and SO_2 emissions per household in one heating season was lower, but CO, CO_2, and NOx increased when semi-coke coal and specified improved stoves were deployed. Most differences were not statistically significant due to the limited samples and large variation, indicating that further evaluation would be needed to make conclusions that could be considered for policy.

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1. Introduction

China suffers from severe air pollution, especially heavy haze episodes during the heating seasons (Liu et al., 2016; Zhang et al., 2017). China currently is the largest producer and consumer of coal in the world. More than 90 million tons of coal are used annually for household energy of which 90% are raw coal (Kerimray et al., 2017; NBSC, 2016). Over 66 million households use coal heating stoves (<50 kW) as space heating appliances in rural China during the cold season, with 70% of this share being traditional and inefficient stoves (CREIA, 2016). By burning low-rank coal without pollution control measures, residential heating stoves can emit much higher (~100 times, based on fuel mass) emissions than industrial boilers (Zhang et al., 2008). Consequently, coal combustion has become the largest contributor to ambient particulate matter (PM) (Duan et al., 2014) and CO_2 (Liu et al., 2015) emissions in China. It is estimated that more than 60% of PM, SO_2, NOx, CO, organic carbon (OC), and black carbon (BC) emissions are attributable to residential raw coal combustion (Zhi et al., 2017a,b), and approximately one million premature deaths annually are caused by household use of solid fuels (Duan et al., 2014; Zhang and Smith., 2007). It was found that the elimination of residential emissions could decrease ambient $PM_{2.5}$ concentration by approximately 40% (Liu et al., 2016a,b). Emissions from rural household coal heating stoves largely contribute to the total emissions from the residential sector and have thus attracted broad public attention (Kerimray et al., 2017; Xue et al., 2016; Zhi et al., 2017a,b).

In recent years, national policies and clean heating technology interventions have been launched to tackle the pollution problem from residential heating (Gao et al., 2016; Liu et al., 2016a,b; Van et al., 2017; Zhang et al., 2010). In 2013, the *National Action Plan on Air Pollution Prevention and Control (2013–2017)* was delivered by the China State Council, restricting annual coal consumption,

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including household consumption, to 3000 Mtce (million ton standard coal equivalent) by 2020 (Jin et al., 2016). Replacing coal with clean energy has been promoted in some developed rural areas, mainly involving natural gas (NG) and electricity (Peng et al., 2017; Qin et al., 2017). Electricity is regarded as clean energy for end users although its generation from fossil fuels may result in the release of copious amounts of toxic emissions into the atmosphere. Nevertheless, it is recognized and widely accepted that coal will continue to be the dominant fuel in China for heating due to an abundance of the resource compared to oil and NG. Cleaner energy interventions have high construction costs and are reserved for higher-cost end uses, and the abundant supplies of coal in China are advantageous for national energy security.

Due to the accessibility and affordability of coal and stoves in rural areas, the introduction of improved stoves coupled with processed coals is a more practical and relevant solution. Moreover, better ignition methods and improving stove ventilation rates may reduce emissions from coal burning (Makonese et al., 2015, 2017a, 2017b; Masondo, 2016). Therefore, improved stoves promotion programs are being carried out around the country using financial incentives, including *Good Coal with Good Stove* or *Clean Heating Program*, which are expected to achieve efficient and clean burning (Zhi et al., 2009). These programs are expected to promote 10 million efficient heating stoves by the end of 2018 to annually save 2.5 Mtce of coal and achieve the reduction of $PM_{2.5}$, CO_2, SO_2, and NO_X by 34, 6500, 18, and 4 thousand-tons, respectively (CREIA, 2016). The successful experience of China's national development and promotion of improved cookstoves can be applied to heating stoves, where nearly 349 million rural households benefited from the largest improved cookstove program ever promoted in the world (Edwards et al., 2007; MOA, 2006).

Although numerous plans were made and steps were taken to guarantee that clean stove programs can yield environmental and economic benefits, a few *so-called* “improved stoves” in previous promotions did emit more PM and CO than the traditional stoves (Edwards et al., 2004). SO_2 and NOx emissions from semi-coke coal burning in some heating stoves were comparable or even higher than those produced by raw coal (Wang et al., 2016). Thus, characterizing these emissions is essential to identify whether real environmental benefits are achieved, especially since semi-coke coals are recently being promoted vigorously in multiple provinces in northern China. However, to our knowledge, there are still no follow-up evaluations on these heating stoves and semi-coke promotion programs.

This field study in rural Zibo, Shandong Province, evaluated the performance of coal heating stoves burning semi-coke coals. Zibo county is suffering from severe air pollution, particularly in cold seasons due to the wide use of raw coal for residential heating demands (MEPA, 2017). An intervention program was initiated by the local government to disseminate semi-coke coals and corresponding improved heating stoves that are specified for the burning of semi-coke coals in the county. These field measurements are expected to: 1) evaluate the efficiency and air pollutant emissions from semi-coke coal combustion in specified improved stoves; 2) evaluate the efficiency and air pollutant emissions for the combustion of raw coal chunks and stoves currently used by the local residents; and 3) ascertain the potential of emission reduction when using improved stoves and semi-coke coal compared to the business-as-usual scenario, which would provide vital evidence for future stove and fuel intervention programs and project evaluations for policy-makers.

2. Materials and methods

2.1. Sampling site and stove-fuel combination

This field study was conducted in January 2017 in the rural Zibo municipality of Shandong Province, which is one of the demonstration villages for the deployment of clean coal and high-efficiency heating stoves. It was reported that 11 thousand stoves and 620 kilotons of semi-coke chunk and coal briquette were distributed by the local government in 2016, supported with a subsidy of 97 million Chinese Yuan (MGW, 2016). In the studied region, the heating season lasts approximately 4.5 months, from mid-October to the beginning of March of the following year. Local residents have the traditional habit of burning raw coal for cooking and heating, enabling them to skillfully operate the promoted stoves with semi-coke chunk during our measurement period. The raw coal used was bituminous coal chunk, which is widely used in rural northern China. The proximate and ultimate analyses of semi-coke and raw coal chunks can be seen in Table 1.

There are three major types of heating stoves in the studied village. Pictures of these stoves are shown in Fig. 1a–c. The first one is the traditional one-chamber radiant heating stove (**Tra.**, accounting for ~30% of the total stoves in the village), which was only able to support home heating in one room. The second type of stove is upgraded with the addition of a secondary air supply and water cycling system to warm more rooms (**Imp.(I)**, accounting for ~50% of the total stoves in the village). The first and second types of stoves were initially designed for raw coal chunk (RC) and are extensively used in northern China, so the combination of Tra.+RC or Imp.(I)+RC was usually regarded as the baseline to ascertain the reduction potential of emissions of *Clean Heating Programs*. The third stove (**Imp.(II)**, accounting for ~20% of the total stoves in the village) has a similar appearance to Imp.(I), but was designed for semi-coke coal (SC). With the integrated functions of cooking and heating, all of these stoves are top-loaded, natural draft, and installed with outdoor chimneys. Most stoves can burn continuously for an entire winter period with one ignition. Detailed descriptions of each stove are given in **S1** and Table S1.

Raw coal was originally used before semi-coke was introduced in the studied village. The raw coal chunk and semi-coke chunk were transported from Yangquan, Shanxi Province and Shenmu, Shaanxi Province, respectively. They are the main coal-mining regions, accounting for more than 10% of the market share in China. Pictures of the coals can be seen in Fig. 1d–e. Semi-coke is a low-volatile and low-ash compound coal product, created through the carbonization process from bituminous coal. The carbonization process is considered to be an important approach for reducing $PM_{2.5}$, SO_2, and NOx. Household energy conditions are subject to income, resource availability, and tradition. Because semi-coke is believed to be clean and raw coal is cheap, the stove-fuel mismatching cases of an Imp.(I) stove burning semi-coke chunk and an Imp.(II) burning raw coal chunk were also found in addition to the regular cases of Tra.+RC, Imp.(I)+RC, and Imp.(II)+SC. Thus, five stove-fuel combinations could be observed in the studied area: 1) Tra.+RC; 2) Imp.(I)+RC; 3) Imp.(I)+SC; 4) Imp.(II)+RC, and 5) Imp.(II)+SC.

Table 1
The proximate analyses, ultimate analyses, and heating values for raw coal chunk and semi-coke in this study.

Coal	HV, MJ/kg	Proximate Analysis (%) [a]				Ultimate Analysis (%)			
		M_{ar}	A_d	V_d	FC_d	C	H	N	S
Raw coal	20.413	8.95	17.02	58.80	24.18	56.95	3.34	0.59	0.20
Semi-coke	28.936	5.66	6.52	11.98	81.50	77.68	1.18	0.71	0.30

A_d, V_d, and FC_d represent the dry basis ash, volatile matter, and fixed carbon content, respectively.
C, H, N, and S represent the carbon, hydrogen, nitrogen, and sulfur content, respectively.
[a] HV and M_{ar} represent the received basis heating value and moisture content, respectively.

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