


Cite this: *RSC Adv.*, 2022, 12, 20886

Comparative evaluation of thermal and emission performances for improved commercial coal-fired stoves in China

Riaz Ahmad,[†] Yuguang Zhou,[†] Chao Liang,^{afg} Gang Li,^{afg} Nan Zhao,^{afg} Adnan Abbas,^a Fan Yu,^d Lianliang Li,^b Jue Gong,^b Duoyi Wang,^c Yanming Yang,^c Zixuan Tang,^e Muhammad Sultan,^h Chao Sunⁱ and Renjie Dong^{afg}

The extensive use of traditional cooking stoves to meet daily cooking and heating requirements has highlighted the serious problem of indoor and outdoor air pollution. This study evaluates seven improved coal-fired space-heating and cooking stoves and compares them with a widely used stove of an older design, selected as a baseline reference. The seven stoves were selected from a range of candidate improved stoves submitted by manufacturers for testing as part of the air quality improvement in the Hebei Clean Air Project, Hebei Province, China. Stove performance was evaluated when burning raw coal and coal briquettes during the high and low power stages respectively. All seven improved cooking stoves surpassed the baseline stove in combined heating and cooking thermal and emission performance. Among the improved cooking stoves, Model 2-TL was found to have the highest average thermal efficiency, $87.2 \pm 0.5\%$, when burning coal briquettes at high and low power. The lowest emission of $\text{PM}_{2.5}$ was $0.94 \pm 0.5 \text{ mg MJ}_{\text{NET}}^{-1}$, CO $0.55 \pm 0.28 \text{ g MJ}_{\text{NET}}^{-1}$, and CO/CO_2 $1.1 \pm 0.6\%$, respectively. It is concluded that the use of these improved heating and cooking stoves should be promoted for daily cooking and heating requirements. This strategy will not only save fuel to the benefit of the household, but widespread adoption could contribute to significant reductions of CO and $\text{PM}_{2.5}$ emissions in Hebei Province.

Received 30th May 2022
Accepted 16th June 2022

DOI: 10.1039/d2ra03364j

rsc.li/rsc-advances

1 Introduction

Nearly three billion individuals in developing nations depend on solid fuels, particularly biomass, for their cooking, heating, and even lighting necessities.^{1,2} More than 80% of China's population lives in rural areas, and 95% of them use coal, wood

and other biomass for cooking and heating.^{3–5} Though household heating with biomass and coal is common in northern China, the contribution of space heating stoves to ambient air pollution has not been well studied.⁶

The extensive use of and dependence on conventional cooking stoves is the prime reason for the perilous quality of indoor air.^{7,8} Indoor air pollution (IAP) is a complex mixture of solid particles, liquid droplets and gases which, when inhaled, causes or exacerbates respiratory ailments.^{9,10} IAP has been attributed to be a factor in 3 to 7 million premature deaths annually, with the attribution of cardiorespiratory illness being a major factor.^{11–13} Studies have demonstrated that lung cancer could in large part be related to the burning of solid fuels in poorly ventilated homes for space heating and cooking.^{14,15} The products of incomplete combustion of fuel in traditional stoves have more global warming potential than carbon-dioxide.^{16,17} Due to inefficient traditional stoves and low-quality fuel, a high level of smoke is produced as a result of incomplete combustion.^{18,19} Depending on the fuel composition, there is the possibility of releasing flue gases with a high concentration of SO_x (sulfur oxides) and NO_x (nitrogen oxides) due to the impracticality of adding desulphurization and denitrification equipment to a domestic stove. The adoption of improved cooking stoves in rural households can reduce black carbon

^aBioenergy and Environmental Science and Technology Laboratory, College of Engineering, China Agricultural University, Beijing 100083, China

^bSchool of Artificial Intelligence, Beijing Technology and Business University, Beijing 100048, China. E-mail: ligang@btbu.edu.cn

^cSchool of Ecology and Environment, Zhengzhou University, Zhengzhou, Henan Province 450001, China. E-mail: nan.zhaoca@outlook.com

^dSchool of Economics, Beijing Technology and Business University, Beijing 100048, China

^eSchool of Art and Communication, Beijing Technology and Business University, Beijing 100048, China

^fKey Laboratory for Clean Renewable Energy Utilization Technology, Ministry of Agriculture and Rural Affairs, Beijing 100083, China

^gNational Center for International Research of BioEnergy Science and Technology, Ministry of Science and Technology, Beijing 100083, China

^hDepartment of Agricultural Engineering, Bahauddin Zakariya University, Bosan Road, Multan 60800, Pakistan

ⁱShandong Warm Valley New Energy & Environ. Protection Technology Co., Ltd, Yantai, 264001, China

[†] Riaz Ahmad and Yuguang Zhou contributed equally to this work.



(BC) by 47%.²⁰ In Hebei Province of China, air contamination in the southern urban areas is significantly worse than in the north. Particulate matter (PM) is the most noteworthy air pollutant, with SO₂ and NO_x also being significant.²¹ Coal-fired industrial and residential boiler emissions are the key drivers of air pollution control measures being implemented in the Beijing, Tianjin and Hebei Province (BTH) region. China plans to replace most residential coal stoves in northern China with clean heating devices by 2021 in response to severe air pollution. The replacement of coal stoves began in the BTH region and is spreading throughout northern China. It is beneficial for both air quality and public health to remove coal stoves, as well as reducing greenhouse gas emissions.²² Emissions of SO₂, PM, PM₁₀ (coarse PM with aerodynamic diameter ≤ 10 μm), and PM_{2.5} (fine PM with aerodynamic diameter ≤ 2.5 μm) from coal-fired residential and industrial boilers in 2012 were respectively, 9 × 10⁵ tons, 3 × 10⁵ tons, 3 × 10⁵ tons, 1 × 10⁵ tons and 0.8 × 10⁵ tons.²³

Coal has been the most significant energy source of China, and in the near future it will be a prime energy source in other developing nations. However, its improper utilization is closely related to serious concerns about air pollution.^{24,25} At present, improperly combusted coal is the primary contributor to air pollution appearing in the form of a heavy smog in numerous urban areas, often called a “haze”.^{26,27} Haze remediation measures have included the adoption of district heating systems and conversion of residential biomass stoves to liquefied petroleum gas (LPG).²⁸

The incomplete combustion of biomass has also been a source of indoor pollution.^{29–32} The pollution created by burning biomass badly in traditional stoves includes carbon monoxide, PM_{2.5} and black carbon.³³ These health and environmental challenges can be reduced by using modern, efficient stoves with greatly reduced emission factors.^{34,35} In the rural regions of developing nations, the general population appreciates “low-quality” inexpensive coal to meet their everyday cooking and warming requirements because of cost.^{36,37}

This paper reports the results of an investigation into the performance of seven modern commercial coal stoves and compares their performance with an older baseline stove. This information could be useful as evidence-based policy support for planning the air quality management. This was done using an online (real-time) stove performance testing system. The measured data were used to calculate the total pollutant mass discharged using a test method used previously to assess the performance of clean stoves in China and abroad. Seven commercially available stoves were compared to the baseline model while burning two fuels: semi-coked coal briquettes and *Shenmu* raw coal. All these stoves were coal-fired low-pressure boilers (LPB) with integrated cooking and water heating suited to the requirements of rural households in Hebei Province, China.

2 Materials and methods

A clean stove promotion project has been undertaken as part of the Hebei Clean Air Project. An assessment of the performance of candidate stoves was carried out at the Biomass Stove Testing

Laboratory at China Agricultural University. Seven commercial improved stoves were anonymized with the labels 1-TL, 2-TL, 3-TL, 4-TL, 5-TL, 6-FL, 7-FL and the “Baseline” stove (Table 1). They were tested using raw coal with an average size of 40–60 mm and semi-coked coal briquettes with an average size of 50 mm. Their thermal efficiency and emissions were assessed. The baseline stove had been in continuous use for about ten years. The baseline data were used to characterize current household heating requirements. During these tests, measurements were recorded every 10 seconds and stored on a computer for analysis.

A gas analyzer (MRU MGA5/Vario Plus, Germany) was used to measure the concentrations of gases taken directly from the flue. A non-dispersive infrared (NDIR) sensor was used for measuring the concentration of CO₂ gas in ppm, the rest (O₂, CO, NO_x, SO₂) using electrochemical cells. The temperatures measured with K-type thermocouples are logged every one second. An ultrasonic flowmeter was used to measure the heating water flow rate through the heat exchanger in litres per second. The particulate matter was measured by a DustTrak DRX aerosol monitor (Model 8533) (mg m^{−3}). The DustTrak has internal zero calibration and simultaneously reports PM₁, PM_{2.5}, PM₄ and PM₁₀. The stove was set on an electronic mass balance and all instrument functions were checked in advance. The stove testing system is shown in Fig. 1. The fire was ignited with pre-weighed paper and wood and small pieces of coal. The experiment included a total of 48 tests: triple replications were made for each of 16 stove–fuel combinations.

2.1 Fuel preparation

Two fuels were used: semi-coked briquettes and raw coal. The briquettes are claimed to be a “low smoke fuel”. The raw coal was broken into smaller pieces approximately 40–60 mm by hammering to mimic typical user behavior. In the countryside, fuel markets typically sell oviform and oblate spheroidal coal briquettes with a diameter of ≈ 50 mm and raw coal ranging from 40 to 60 mm across. The replacement of “low-grade” coal with either semi-coked coal or biomass briquettes is claimed to be an effective method for mitigating SO₂ emissions.³⁸

The calorific value, moisture content, volatile matter fraction and elemental composition were analyzed by Northern China Electric Power University using the methods in the relevant Chinese national and industrial standards: Agricultural Standard of the People's Republic of China (NY/T 1881.1-2010) National Standard of the People's Republic of China (GB/T 28731-2012) – (GB/T 28734-2012).

2.2 Stove testing and test procedure

The laboratory at the China Agricultural University has equipment to dilute and dehydrate the sample of products of incomplete combustion prior to measurement across a wide range of concentrations. The dilution ratio can be varied from 3 : 1 to 100 : 1 as required, to keep the concentration within the operating limits of the DustTrak DRX aerosol monitor (0.001–150 mg m^{−3}) (Fig. 1). After ignition, the dilution remains constant during each test to avoid errors. The variable dilution



Table 1 Details and identification of stoves used in the study

Stove ID number	Identification	Type
Base	Baseline stove	Top loading, handmade, more than ten years old, no secondary air supply hole for low power running, one burner
1-TL (top load)	Small orange	Top loading, commercial ICS, one burner, primary air supply for high and low power
2-TL (top load)	Light orange grey	Top loading, commercial ICS, one burner, primary and secondary air supply for high and low power
3-TL (top load)	Blue with two pots	Top loading commercial ICS, two burners, primary and secondary air supply for high and low power
4-TL (top load)	Big orange	Top loading commercial ICS, one burner, primary air hole in ash removal door and secondary air on the upper side of the ash chamber supply for high and low power
5-TL (top load)	Big green	Top loading commercial ICS, one burner, primary air hole in ash removal door and secondary air supply with the external holes in the combustion chamber for high and low power
6-FL (front load)	Grey	Front loading commercial ICS, one burner, primary air hole in ash removal door for high and low power
7-FL (front load)	Small green	Front loading commercial ICS, one burner, primary air supply hole for high and low power in ash removal door

system overcomes the limitation of fixed dilution systems in that the systematic “error” is overcome through the use of a dilution and humidity monitoring apparatus that simultaneously overcomes the problems created by fixed dilution systems and variable stack humidity. The instrument was calibrated in the fashion described. That calibration is maintained by the correct use of the variable dilution system. The flue gases are diluted by air containing nearly no CO, CO₂ or water vapor

(dew point < −60 °C). The use of this specially prepared dilutant preserves the calibrated accuracy of the optical measurement system even if the humidity of the source particles varies widely. The humidity is controlled (by adjusting the dilution if necessary) in a typical range of 15–30%. The dilution rate is calculated per 10 seconds by comparing the concentration of CO₂ before and after dilution, factoring for ambient CO₂. Diluted and undiluted flue gases and diluted particle measurements are

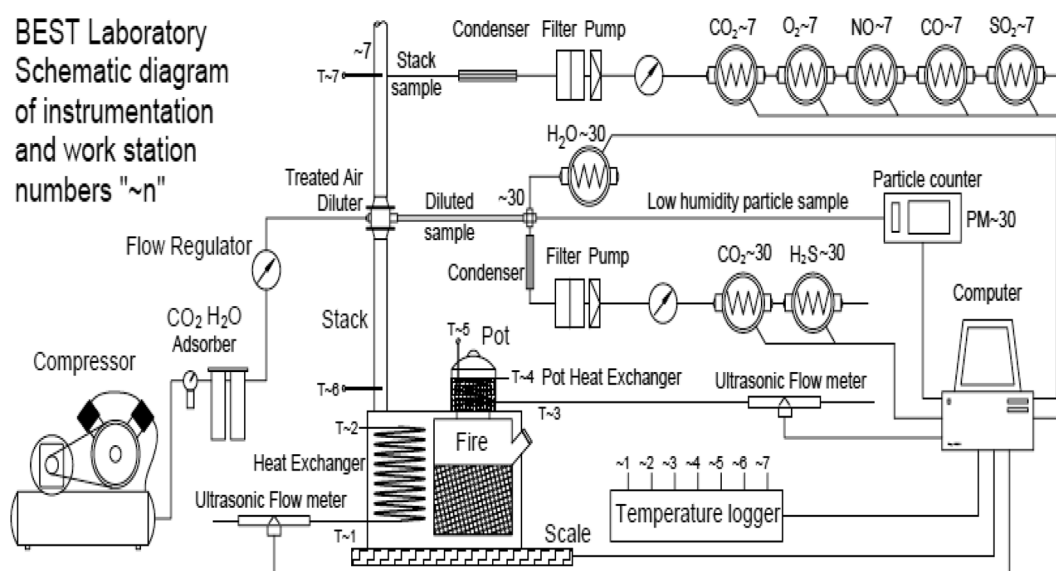


Fig. 1 Schematic diagram of the online testing system with work station ~numbers (the H₂O is a RH sensor. The ~30 and ~7 etc. are work station numbers as indicated on the drawing).



recorded using a data acquisition system. Of the more than 120 approved models commonly available in Hebei Province, 8 were selected; one being the baseline product as shown in Fig. 2.

Instrument measurements were recorded every 10 seconds and included: mass change of the system, inlet and outlet water temperature in the space heating heat exchanger and the cooking pot heat exchanger, the flow rate of the coolant in each, the temperature of the uncirculated water in the cooking vessel, PM and trace gas emissions, ambient and diluted gas humidity, numerous other temperatures and the ambient air pressure. During the high power test, the flow of coolant through the space heating heat exchanger was adjusted for high and low power to maintain an output temperature of approximately 50 ± 20 °C. Without monitoring this variable, the cooling water might boil at high power which does not happen in typical use. On the other hand, having a low ΔT (change in temperature) on the heat exchanger reduces the accuracy of calculated results. The concentrations of trace gases H_2 , SO_2 , NO , CO , CO_2 , O_2 were measured directly from flue while in the diluter measurements included CO_2 , H_2O , H_2S . The calculated outputs include the

heating and cooking efficiency, emission rates and the combined cooking and heating efficiency were performed according to Beijing Municipal Standard (DB11/T 540-2008). The fire was set according to the manufacturer's instructions.

2.3 Calculations

An adequate quantity of fuel sufficient for the entire experiment was estimated using the following formula:

$$M_{\text{fuel}} = 3.6 \left(\frac{t_{\text{test}} P_{\text{rNET}}}{\text{LHV}_{\text{fuel}} \eta_{\text{tr}}} \right) \times 1.1 \quad (1)$$

where: M_{fuel} is the mass of the fuel set aside [kg]; 3.6 converts $J \text{ s}^{-1}$ to kJ h^{-1} ; t_{test} is the testing duration [h]; P_{rNET} is rated heating power [kW_{NET}]; LHV_{fuel} is Lower Heating Value of the fuel as received (AR) [MJ kg^{-1}]; η_{tr} is the rated high power thermal efficiency [%]; the factor of 1.1 is due to the 10% safety margin so as not to run out before the test ends.

If the rated thermal efficiency was not available, but the stove had passed the Beijing Municipal Standard (DB11/T 540-2008),

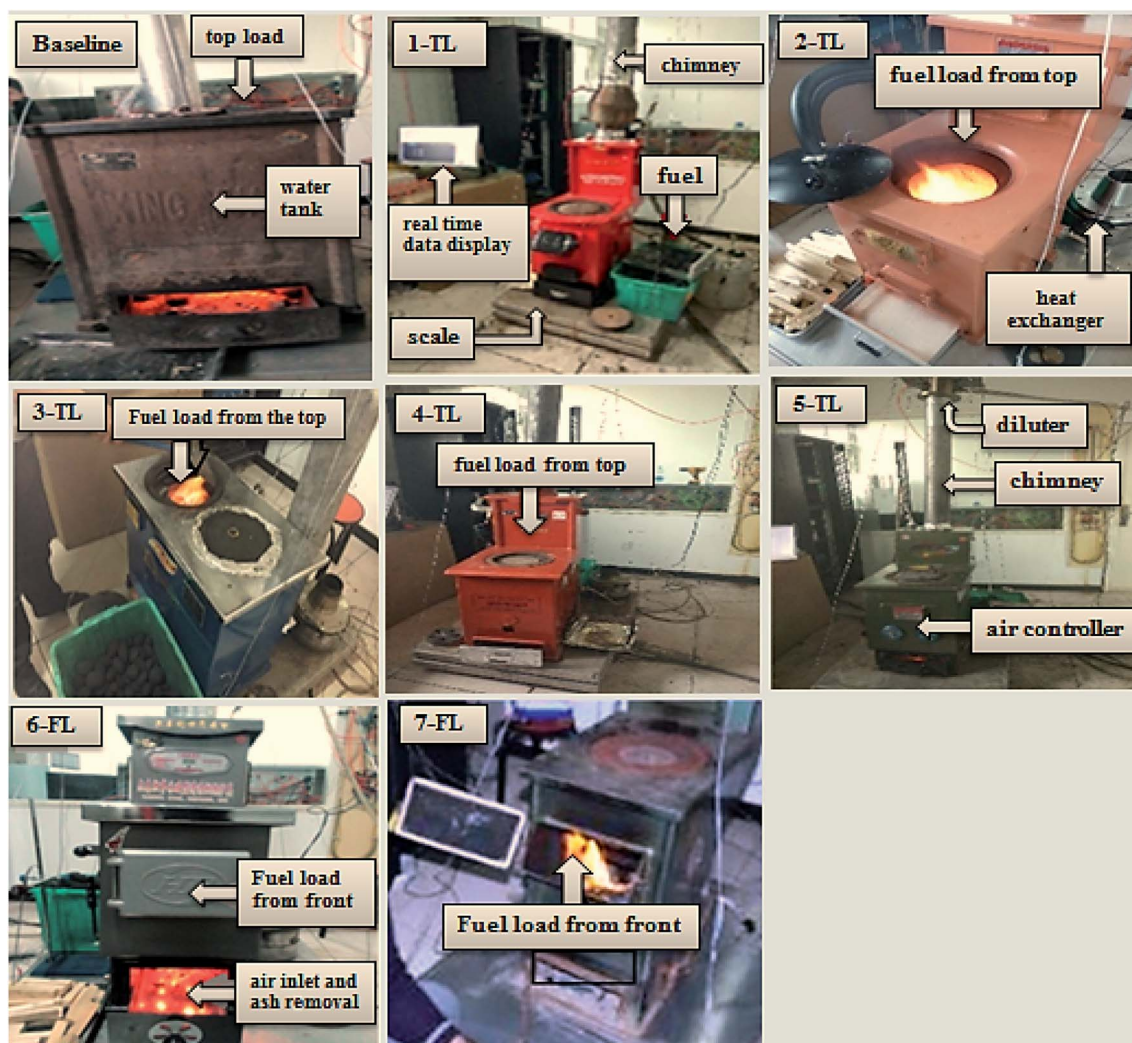


Fig. 2 Stoves used in the current study with different feeding method and design.

a default thermal efficiency value of 60% was assumed based on the fact that the stove had been allowed to enter the market.

The stoves performance parameters were calculated using the equations listed below.

Q_1 , the heat gained by the space heating heat exchanger was calculated using eqn (2).

$$Q_1 = C_{p,w} (T_2 - T_1) \Delta t \text{ flow rate} + \left(\frac{C_{p,\text{tube}}}{C_{p,w}} m_{\text{exch}} + m_{w,\text{exch}} \right) C_{p,w} \Delta \bar{T}_{\text{exch}} \quad (2)$$

$$\Delta \bar{T}_{\text{exch}} = \left(\frac{T_2 + T_1}{2} \right)_{t_f} - \left(\frac{T_2 + T_1}{2} \right)_{t_i} \quad (3)$$

where $C_{p,w}$ is the specific heat capacity of water [J g^{-1}]; T_1 is the heat exchanger inlet temperature [$^{\circ}\text{C}$]; T_2 is the heat exchanger outlet temperature [$^{\circ}\text{C}$]; m_{exch} is the mass of the heat exchanger [g]; $m_{w,\text{exch}}$ is the mass of the water in the heat exchanger [g]; $\Delta \bar{T}_{\text{exch}}$ is the change in average temperature of the water in the heat exchanger [$^{\circ}\text{C}$]. The rated heating power (P_{rNET}) was calculated using the eqn (4):

$$P_{\text{rNET}} = \frac{Q_1}{1000(t_f - t_i)} \quad (4)$$

where t_f and t_i are final and initial time [s], respectively.

The heat gained by the cooking pot (Q_2) and its uncirculated contents are calculated using the eqn (5) as follows:

$$Q_2 = C_{p,w} \Delta T_5 \quad (5)$$

$$\Delta T_5 = (T_5)_{t_{n+1}} - (T_5)_{t_n} \quad (6)$$

where ΔT_5 is change in temperature of the cooking pot and its uncirculated contents, the term $(n + 1) - n$ is the measurement interval of 10 seconds.

The heat gained (Q_3) by the coolant flowing through the cooking pot heat exchanger (tube), the heat exchanger tube, and the coolant contained within that tube is calculated by eqn (7).

$$Q_3 = C_{p,w} (T_4 - T_3) \Delta t \text{ flow rate} + \left(\frac{C_{p,\text{tube}}}{C_{p,w}} m_{\text{tube}} + m_{w,\text{tube}} \right) C_{p,w} \Delta \bar{T}_{\text{tube}} \quad (7)$$

$$\Delta \bar{T}_{\text{tube}} = \left(\frac{T_4 + T_3}{2} \right)_{t_{n+1}} - \left(\frac{T_4 + T_3}{2} \right)_{t_n} \quad (8)$$

where $\Delta \bar{T}_{\text{tube}}$ is the change in the average temperature of the tube and the coolant contained in the tube. The total heat gained (Q_4) by the cooking system during the test period was calculated using (eqn (9)) as follows:

$$Q_4 = Q_2 \sum_{t_i}^{t_f} + Q_3 \sum_{t_i}^{t_f} \quad (9)$$

The total useful heat (Q_t) delivered is the sum of the space heating and cooking energy is given in MJ by eqn (10) as follows:

$$Q_t = \frac{Q_1 + Q_4}{10^6} \quad (10)$$

The total chemical energy (U_t) available from the fuel fed into the stove during the test is given in MJ by eqn (11) as follows:

$$U_t = B Q_{\text{net,var}} + B_0 Q_{\text{net,var1}} \quad (11)$$

where B is the mass of fuel fed [kg]; $Q_{\text{net,var}}$ is the LHV of the fuel as received [MJ kg^{-1}]; B_0 is the mass of kindling material [kg]; $Q_{\text{net,var1}}$ is the LHV of the kindling materials as received [MJ kg^{-1}].

The percentage of useful heat delivered by the stove Q_t divided by the total heat available from the fuel fed U_t , indicates the fraction of energy utilization. Before starting the test, the pre-weighed fuel was placed in a container on a platform that was larger than the stove to adequately limit such possible drying. The space between the stove and the fuel was about 15 cm, which didn't affect moisture and prevented the fuel from drying out during use. The test continued for 16 hours from ignition to the end, and the cooking phase was started three hours after ignition. The time was noted before and after the cooking phase in order to separately calculate the cooking efficiency. The change in mass was determined from the scale data which enables the determination of the fuel mass consumed during each of multiple space heating and cooking phases. The thermal efficiency (η_c) of cooking was calculated as a percentage using eqn (12). The space heating efficiency (η_h) was calculated as a percentage using eqn (13). The overall system efficiency (η_t) for cooking and heating was calculated using eqn (14).

$$\eta_c = \frac{Q_4}{U_t} 100 \quad (12)$$

$$\eta_h = \frac{Q_1}{U_t} 100 \quad (13)$$

$$\eta_t = \frac{Q_t}{U_t} 100 \quad (14)$$

The $\text{PM}_{2.5}$ emission factor ($\text{EF}_{\text{PM}_{2.5}}$) was calculated in $\text{mg MJ}_{\text{NET}}^{-1}$ using eqn (15).

$$\text{EF}_{\text{PM}_{2.5}} = \frac{\text{TPM}_{2.5}}{Q_t} \quad (15)$$

where $\text{TPM}_{2.5}$ is the total mass of PM emitted [mg] which is calculated using (eqn (16)); Q_t is the total useful heat energy (eqn (10)) [MJ].

$$\text{TPM}_{2.5} = \text{PM}_{2.5} D_r V_{\text{dil}\sim 1} \quad (16)$$

where $\text{TPM}_{2.5}$ is the total mass of $\text{PM}_{2.5}$ reported during the sampling interval [mg]; D_r is the dilution ratio between the stack sample and the diluter sample and is estimated using eqn (17). $V_{\text{dil}\sim 1}$ is the volume of emissions in the stack [m^3], including excess air, created by the mass of fuel burned as given by eqn (18).



$$D_r = (\text{CO}_{2\text{stack}} - \text{CO}_{2\text{ambient}}) / \left(\frac{\text{CO}_{2\text{diluted}} (\text{CO}_{2\text{stack}} - \text{CO}_{2\text{ambient}})}{\text{CO}_{2\text{stack}}} \right) \quad (17)$$

$$V_{\text{dil} \sim 1} = V_{\text{sto}} \Delta m_{\text{fuel}} \lambda \quad (18)$$

where Δm_{fuel} is the change in mass of fuel fed [kg]; V_{sto} is the stoichiometric volume gases produced by the combustion of 1 kg of fuel (AR) [m^3]; λ is the total air demand factor providing both used and unused oxygen. The CO emission factor was calculated using eqn (19)

$$\text{EF}_{\text{CO}} = \frac{m_{\text{CO}}}{Q_t} = \frac{m_{\text{CO}} \times V_{\text{dil}}}{Q_t} \quad (19)$$

where m_{CO} is the mass of CO emitted during the sampling interval [g]; m_{CO} is the mass concentration of CO [g m^{-3}]. The $\text{CO} \left(\frac{\text{g}}{\text{m}^3} \right)$ is converted into $\text{CO}_{\text{ppm(v)}}$ using eqn (20)

$$\text{CO} \left(\frac{\text{g}}{\text{m}^3} \right) = \text{CO}_{\text{ppm(v)}} 0.0012334 \quad (20)$$

where 0.0012334 is the conversion factor.

The fuel saving was calculated using (eqn (21)).

$$\text{Fuel savings} = [1 - (\text{base efficiency/improved efficiency})] \times 100 \quad (21)$$

2.4 Apparatus

A catalogue of test indicators, instruments and testing principles is given in Table 2. In order to evaluate the performance of the stoves, sixteen hour tests were first conducted combining China's relevant standard methods with observed local behaviors. The test sequence comprises various stages informed by observing the cooking and heating behavior of rural consumers in Hebei Province, China. The details of this protocol are provided in Table 3.

3 Results and discussion

3.1 Analyses of the fuels

Both fuels were analysed for their elemental composition, moisture content, volatile matter fraction and higher heating value (HHV) (Table 4). The moisture content of raw coal was higher than that of semi-coked briquettes. The volatiles content of the semi-coked coal briquettes was low. The nitrogen content of the briquette was higher than that of the raw coal.

3.2 Thermal performance

The test results show that for each fuel-stove-use pattern, all stoves except the baseline and 5-TL met the thermal efficiency requirement ($\geq 60\%$) of the relevant standard (DB11/T 540-2008). The thermal and emissions performance indicators are presented in Table 5 according to the relevant standard (DB11/T 540-2008). The thermal efficiencies for all eight stoves are

presented in Fig. 3. The results show that the new, project-approved stoves had much higher thermal efficiencies than the baseline stove. The thermal efficiency of the baseline stove was poor, even though sometimes it had good combustion efficiency. The failure to perform is due to the low heat exchange surface area per rated kW compared with the new stoves. The average baseline stove efficiency was $48.8 \pm 1.4\%$ burning coal briquettes and $38.5 \pm 2.8\%$ burning raw coal. The average fuel savings, calculated using eqn (21) for each stove and then averaged, was 44%. Stove 2-TL was found to be the most efficient ($87.2 \pm 0.5\%$) burning briquettes and $62.9 \pm 0.6\%$ burning raw coal. The least efficient stove was the 5-TL with an average thermal efficiency of $61.2 \pm 3.2\%$ and $52.6 \pm 4.2\%$ burning coal briquettes and raw coal respectively. Despite these low values, stove 5-TL will still save 1/3rd of the fuel compared with the baseline stove. Previously, mixed results have been reported with some authors finding no significant differences between some stoves and fuel types.⁸

3.3 Emission measurement

3.3.1 Particular matter ($\text{PM}_{2.5}$). The emission performance results (Fig. 4) show that the average (for high and low power) $\text{PM}_{2.5}$ emitted from the baseline stove was $9.4 \pm 0.4 \text{ mg MJ}_{\text{NET}}^{-1}$ burning raw coal while burning semi-coked briquettes it was $2.5 \pm 0.4 \text{ mg MJ}_{\text{NET}}^{-1}$. Stove 2-TL was better for raw coal: $1.1 \pm 0.6 \text{ mg MJ}_{\text{NET}}^{-1}$ but significantly worse for burning briquettes: $5.2 \pm 0.6 \text{ mg MJ}_{\text{NET}}^{-1}$. All the improved stoves produced less $\text{PM}_{2.5}$ than the baseline model with stove 6-FL emitting the least: $1.0 \pm 0.7 \text{ mg MJ}_{\text{NET}}^{-1}$ while burning briquettes followed by 4-TL at $1.6 \pm 0.6 \text{ mg MJ}_{\text{NET}}^{-1}$ and 3-TL at $1.1 \pm 0.3 \text{ mg MJ}_{\text{NET}}^{-1}$.

The average $\text{PM}_{2.5}$ emissions when burning raw coal for the other stoves were 3-TL: 3.2 ± 1.0 , 1-TL: 5.2 ± 0.6 , 5-TL: 2.7 ± 0.5 and 6-TL: $6.5 \pm 0.3 \text{ mg MJ}_{\text{NET}}^{-1}$. Li *et al.*³⁹ reported that in China, the average emission of $\text{PM}_{2.5}$ declined some 92% when semi-coke briquettes were used as fuel in traditional stoves. This study shows that a $40 \pm 1.1\%$ reduction can be achieved by replacing the baseline stove with a Model 2-TL while continuing to burn raw coal. A similar variation in combustion quality between high and low power has been reported for the same types of fuel.⁴⁰

3.3.2 CO/ CO_2 ratio. The lower the CO/ CO_2 ratio, the more complete the combustion of carbon. The CO/ CO_2 ratios during high power for the baseline and 5-TL stoves burning coal briquettes (Fig. 5) were almost equivalent: $7.4 \pm 0.7\%$ versus $7.1 \pm 0.8\%$, respectively. The stove 2-TL, the best performing stove on this metric, scored a CO/ CO_2 ratio of $1.1 \pm 0.3\%$, burning coal briquettes and $1.4 \pm 0.4\%$ burning raw coal. The average CO/ CO_2 ratios for stoves burning raw coal were all higher than when burning briquettes: 1-TL: $3.1 \pm 0.5\%$, 3-TL: $3.5 \pm 0.5\%$, 4-TL: $3.7 \pm 1.1\%$, and 5-TL: $6.4 \pm 0.5\%$. Burning briquettes, the scores were, 1-TL: $3.1 \pm 0.5\%$, 3-TL: $3.5 \pm 0.5\%$, 4-TL: $3.7 \pm 1.1\%$, and 5-TL: $6.4 \pm 0.5\%$. Stoves 6-FL and 7-FL had better performance than the baseline stove during high power operation ($2.3 \pm 0.6\%$ and $1.6 \pm 0.3\%$, respectively), but were worse ($3.7 \pm 0.6\%$ and $3.7 \pm 1.1\%$, respectively) when operated at low



Table 2 Description of test indicators, equipments and testing principle^a

Test indicators	Unit	Equipment	Precision	Measuring range	Test principle
Fuel mass loss	g	Straw FCN-V10	±0.1%	30–600 kg	Double beam sensor electronic scale
Flue gas (O ₂ , CO ₂ , CO, NO _x , SO ₂) concentration	ppm	MRU Vario Plus	±0.1%	O ₂ , CO ₂ , CO, NO _x , SO ₂ = 0–10 000 vol% EC CO ₂ = 0–30% (NDIR)	CO ₂ used NDIR, others use EC sensors
Particulate matter	mg m ⁻³	DustTrak DRX Aerosol Monitor 8533 Desktop	±0.1% of reading of 0.001 mg m ⁻³ , whichever is greater	0.001–150 mg m ⁻³	Light scattering; simultaneously reporting size-segregated mass fraction concentrations corresponding to PM _{1.0} , PM _{2.5} , respirable, PM ₁₀ and total PM
Analysis of flue gas concentration of diluents: CO ₂ , H ₂ O, H ₂ S	ppm	DP00112/DP00118 TESTO 6681+6614	±2% FS	0–30 000 ppm	CO ₂ using NDIR, H ₂ S using EC sensors, H ₂ O using a humidity sensor
Determination of water flow	ml s ⁻¹	TUF-2000P	±1%	0 ± 10 m s ⁻¹	Ultrasonic flow measurement
Temperature	°C	Thermocouple	±0.2 °C	–270 to 1260 °C	Thermocouple thermo electromotive force

^a Note: NDIR = non-dispersive infra-red; MV = measured value; FS = full scale reading; EC = electrochemical.

power. Interestingly, these two stoves were also superior to all the others when burning raw coal during both high and low power operation. It is observed that all stoves operating at high

power had relatively good CO/CO₂ ratios but the combustion quality deteriorated as the burn rate and combustion temperatures decreased. A similar variation in coal combustion quality

Table 3 Description of >16 hour test including ignition and end stages

Testing stage	Duration (h)	Purpose	Reason
Ignition and adjustments	Depends on the ignition	Start the ignition and adjust the stove accurately	The test begins with ignition of the fuel and with a burning period of approximately 30 minutes while the stove is adjusted for best performance. Because the stove is kept burning over the entire heating season, ignition occurs only once, hence the ignition phase and the fuel burnout phase are not included when comparing and evaluating stoves in this context
High power	2	Cooking breakfast	The purpose of the high power after ignition is to make breakfast within two hours and also for space heating
Low power	10	Space heating	The fully loaded stove is run at low power for 10 hours for space heating. Stove power is adjusted by controlling the inlet air
Cooking and heating at high power	1	Cooking dinner	After 10 h low power, the stove was run at high power for evening cooking purposes for one hour duration
High power	3	Space heating	After cooking the stove is operated on high power for three hours to warm the room for comfortable sleep for the household
End stage	Depends on the fuel burning	Test end	Ending process depends on the fuel burned completely after the three hour high power phase



Table 4 Industrial analysis and elemental analysis of fuel^a

Content	Raw coal	Briquette coal
$M_{ar}/\%$	9.04	3.5
$A_{ar}/\%$	5.7	15.7
$V_{ar}/\%$	27.14	10.2
$FC_{ar}/\%$	58.14	70.6
$Q_{net,ar}/MJ\ kg^{-1}$	17.41	25.89
$C_{ar}/\%$	67.5	60.3
$H_{ar}/\%$	4.5	4.1
$N_{ar}/\%$	0.9	0.84
$S_{ar}/\%$	0.4	0.33
$O_{ar}/\%$	20.4	18.2

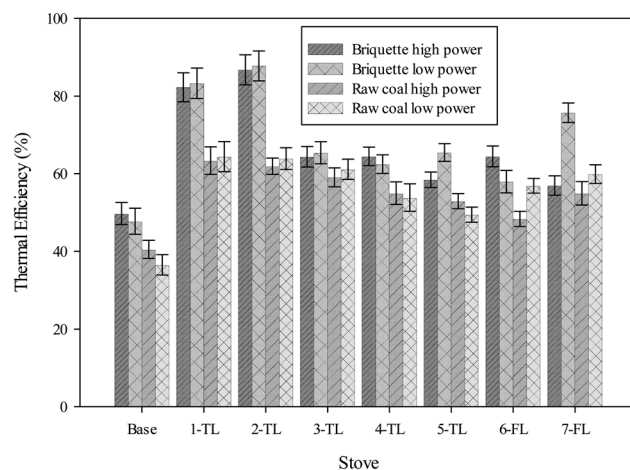
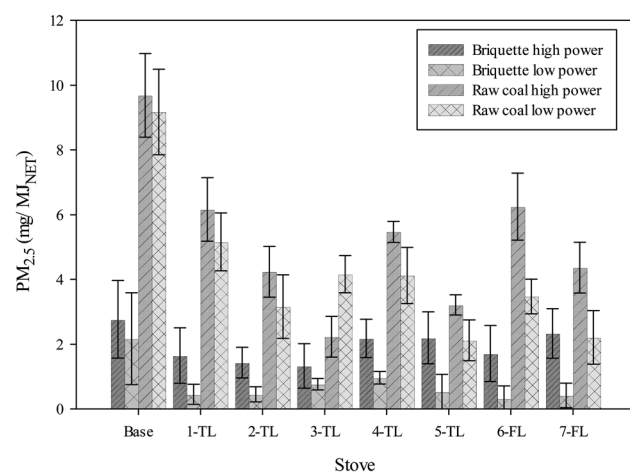
^a Note: ar = as received; M = moisture content; A = ash content; V = volatile matter content; FC = fixed carbon content; C = carbon content; H = hydrogen content; N = nitrogen content; Q_{net} = lower calorific value; S = sulfur content; O = oxygen content.

Table 5 Thermal and emissions performance indicators according to the Chinese testing method (Beijing Municipal Standard, DB11/T 540-2008)

	Unqualified	Qualified	Exceeding requirement
Thermal performance			
Cooking power (kW)	$P_c < 11.3$	$P_c \geq 11.3-50$	$P_c \leq 50$
Thermal efficiency (%)	$\eta_c \geq 60$	$\eta_c \geq 60-65$	$\eta_c \geq 65$
Emission performance			
Smoke mass concentration ($mg\ m^{-3}$)	<10	10–30	<30
NO_x ($mg\ m^{-3}$)	<150	150–150	<150
CO (%)	<0.2	0.2–2.0	<2.0

between high and low power has been reported by reference⁴¹ and for other types of fuel like wood or kerosene⁴² and the inverse for ethanol gel.⁴³

3.3.3 CO emission factor. Fig. 6 shows that the CO emission factors for all improved stoves are lower than the baseline value. The maximum values (8 ± 0.6 and $7.1 \pm 0.6\ g\ MJ_{NET}^{-1}$) were obtained during high and low power operation when burning raw coal in the baseline stove. The minimum emission factors (1.66 ± 0.44 and $0.55 \pm 0.28\ g\ MJ_{NET}^{-1}$) during low and high power operation, respectively, were achieved by stove 2-TL. Overall, the stoves performed better than the baseline product when burning briquettes. Even the baseline stove gave lower emissions burning briquettes at low and high power than for raw coal. In an earlier study,⁴⁴ the CO concentration of $0.07\ mg\ m^{-3}$ when burning “clean” briquettes was significantly lower than when burning the raw coal $4.25\ mg\ m^{-3}$, though we hasten to add that the testing methodology was different. In another study,⁴⁵ the CO emission factor was reported to be between 1200 and $3200\ mg\ MJ^{-1}$ (fuel) for wood stoves and between 92 and $270\ mg\ MJ^{-1}$ (fuel) for pellet stoves, again using a different

Fig. 3 Thermal efficiency of various stoves using briquettes and raw coal. The error bars indicate the standard deviation ($\pm SD$) of three replications.Fig. 4 $PM_{2.5}$ emission performance of improved stove in comparison to baseline.

method. Similar findings with a little variation have been reported in a previous study conducted in the BTH region by Cui *et al.*⁴⁶ Together, these studies indicate that more modern stoves have better combustion quality.

3.4 Overall performance

The overall thermal efficiency improvement, fuel saving and emission reduction performance comparison (Table 6) shows that the maximum thermal improvement and fuel saving $44 \pm 1.1\%$ and $78.6 \pm 0.3\%$ was obtained for the 2-TL stove with coal briquette, the maximum reduction in emissions of $PM_{2.5}$ $63.0 \pm 1.9\%$ and CO $42.2 \pm 0.4\%$ with briquette coal was also achieved for this model. It was found that the firepower of stove 2-TL varied significantly with fuel type ($86.7 \pm 0.8\%$ high power with coal briquettes and $61.9 \pm 1.1\%$ high power with raw coal). This demonstrates that the context of use – stove + fuel + operating sequence – strongly affects the performance.



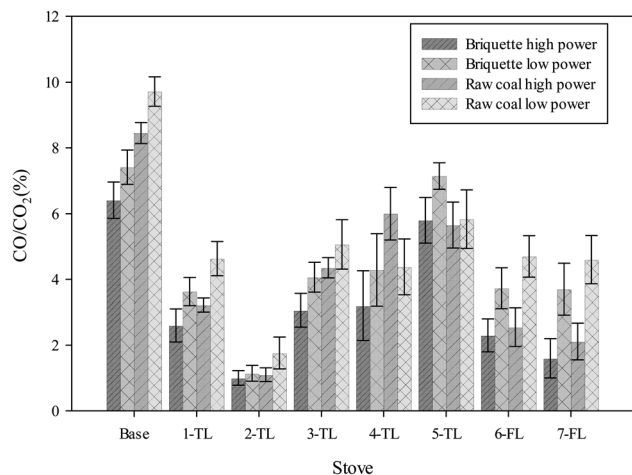


Fig. 5 CO/CO₂ ratio of the improved stove in comparison to the baseline stove with briquettes and raw coal during high power and low power.

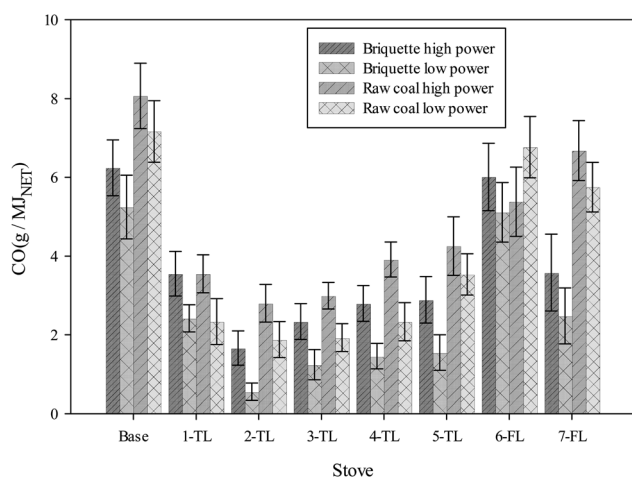


Fig. 6 Emission factors of CO from the improved stoves using briquettes and raw coal in comparison to the baseline stove.

The absolute values for this study differ from others, which can be attributed to differences in the experimental design, the fuels, the testing method and the calculations and metrics employed. Unfortunately, our findings are not directly comparable with other results. In a previous study,⁴⁷ the results showed improved stove reduced emissions of CO 22%, CO₂ 28% and PM_{2.5} 27% in comparison to a traditional stove.

Previously, mixed results have been reported with some authors finding no significant differences between some stove and fuel types^{48–50} while others^{51,52} reported that improved stoves had significantly better thermal efficiency and reduced emissions similar to our results.

4 Conclusions

This study was conducted to investigate the thermal efficiencies and emissions of seven dual-function cooking and heating

Table 6 Thermal improvement and estimated reduction in emission of various stoves^a

Stoves	Thermal efficiency (%)		Thermal improvement (%)		Fuel saving (%)		PM _{2.5} (mg MJ _{NET} ⁻¹)		Est. PM _{2.5} reduction (%)		CO (g MJ _{NET} ⁻¹)		Est. CO reduction (%)	
	Briq. coal	Raw coal	Briq. coal	Raw coal	Briq. coal	Raw coal	Briq. coal	Raw coal	Briq. coal	Raw coal	Briq. coal	Raw coal	Briq. coal	Raw coal
Baseline	48.8 ± 1.4	38.5 ± 2.8	—	—	—	—	2.5 ± 0.4	9.7 ± 1.3	—	—	5.7 ± 1.2	7.6 ± 1.3	—	—
1-TL	82.8 ± 0.5	64.4 ± 0.6	69.6 ± 0.4	66.2 ± 0.2	41.0 ± 1.2	40.0 ± 1.9	1.0 ± 0.6	6.2 ± 1.1	58 ± 1.4	37.4 ± 0.8	3.5 ± 0.8	5.6 ± 0.9	38.6 ± 0.7	24.4 ± 0.7
2-TL	87.2 ± 0.5	62.9 ± 1.0	78.6 ± 0.3	63.2 ± 0.4	44.0 ± 1.1	38.7 ± 1.6	0.9 ± 0.5	5.1 ± 0.9	63 ± 1.9	47.5 ± 0.7	3.3 ± 0.5	4.8 ± 0.7	42.2 ± 0.4	36.9 ± 0.4
3-TL	64.8 ± 0.5	60.1 ± 1	67 ± 0.3	55.0 ± 0.4	24.7 ± 1.8	35.9 ± 1.9	1.1 ± 0.3	6.5 ± 1.2	56 ± 0.7	33 ± 0.9	4.1 ± 1.1	5.3 ± 0.8	28 ± 0.9	30.3 ± 0.6
4-TL	63.4 ± 1.0	54.4 ± 0.6	65.5 ± 0.5	42.0 ± 0.2	23.0 ± 1.3	29.2 ± 1.6	1.6 ± 0.6	5.8 ± 0.9	36 ± 1.4	40.3 ± 0.7	3.7 ± 0.8	5.9 ± 1.1	35.1 ± 0.7	22.5 ± 0.8
5-TL	61.9 ± 3.4	51 ± 1.7	55.0 ± 1.7	32.4 ± 0.6	21.2 ± 1.6	24.5 ± 1.7	1.4 ± 0.8	6.2 ± 1.2	44 ± 1.9	36.1 ± 0.9	3.9 ± 0.9	5.4 ± 0.8	31.6 ± 0.8	29 ± 0.6
6-FL	61.2 ± 3.2	52.6 ± 4.2	51.7 ± 1.6	35.0 ± 1.5	20.2 ± 1.2	25.9 ± 2.0	1.0 ± 0.7	5.9 ± 1.1	39.2 ± 0.8	47.7 ± 1.2	4.7 ± 1.2	5.7 ± 0.9	17.6 ± 1	25 ± 0.7
7-FL	66.4 ± 9.3	57.4 ± 2.4	72.2 ± 4.6	49.0 ± 0.8	26.6 ± 2.1	32.9 ± 2.4	1.6 ± 1.1	5.4 ± 1.0	44.4 ± 0.8	—	3.5 ± 1.0	6.1 ± 1.2	38.6 ± 0.8	38.6 ± 0.8

^a Note: Thermal and emissions performance indicators are shown in Table 5. Est. = estimated.

stoves burning semi-coked coal briquettes and raw coal. A comparison was also made between the improved stoves and a traditional baseline stove. Sixteen hour tests were conducted to evaluate the thermal and emissions performance. The results show that in general, all the improved stoves were better than the baseline stove but not on all metrics in all cases. The commercially produced model 2-TL stove had the highest thermal efficiency ($87.2 \pm 0.5\%$) and the lowest emissions of $\text{PM}_{2.5}$ $0.94 \pm 0.5 \text{ mg MJ}_{\text{NET}}^{-1}$ and CO $1.1 \pm 0.6 \text{ g MJ}_{\text{NET}}^{-1}$, when burning 50 mm briquettes.

It is concluded that with respect to these improved stove designs, semi-coked coal briquettes produce better performance. The improved stoves had higher thermal efficiencies and lower specific emissions on all metrics, contributing to a cleaner environment, saving fuel expenses, and improving the health of the general population, as well as offering greenhouse gas mitigation co-benefits.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (Grant No. 51806242); the Chinese Universities Scientific Fund (No. 2019TC010); Agricultural Product Quality Inspection Bureau, Ministry of Agriculture and Rural Affairs, China, Agricultural Industry Standard Development Project – “Determination method of major atmosphere pollutants from rural household stoves” (No. 181721301092371112); the Innovation and Entrepreneurship program Yantai Economic & Technological Development Area (2020CYRC2); and Project of Hebei Energy Conservation Inspection and Monitoring Center – “Assessment on the effect of clean space heating replacement in Hebei Province”. We also appreciate for the supports from the Key Laboratory of Clean Production and Utilization of Renewable Energy, Ministry of Agriculture and Rural Affairs, China; National Center for International Research of BioEnergy Science and Technology, Ministry of Science and Technology, China; National First-Class Discipline of Agricultural Engineering; Beijing Municipal Key Discipline of Biomass Engineering; and appreciation to the support for some consumables from Beijing Kunhe Environmental Technology, Co., Ltd.

References

- G. Bensch and J. Peters, *J. Health Econ.*, 2015, **42**, 44–63.
- International Energy Agency (IEA), *World energy outlook*, Paris: International Energy Agency, 2011.
- W. Qu, Z. Yuan, M. Qu and M. Ikram, Iran, *J. Public Health*, 2015, **44**, 625–638.
- G. F. Shen, R. Xiong, Y. S. Zhou, X. Q. Jiao, Z. H. Luo, R. Xiong, W. X. Huang, Y. L. Tian, Y. C. Chen, W. Du, H. Z. Shen, H. F. Cheng, D. Q. Zhu and S. Tao, *Sustainable Horiz.*, 2022, **1**, 100010.
- G. F. Shen, R. Xiong, Y. L. Tian, Z. H. Luo, B. Jiangtulu, W. J. Meng, W. Du, J. Meng, Y. C. Chen, B. Xue, Y. H. Wang, J. Duan, F. G. Duo, L. Fan, T. Z. Huang, T. Z. Ju, F. G. Liu, S. X. Li, X. L. Liu, Y. G. Li, M. Wang, Y. Nan, B. Pan, Y. F. Pan, L. Z. Wang, E. Zeng, C. Zhan, Y. L. Chen, H. Z. Shen, H. F. Cheng and S. Tao, *Natl. Sci. Rev.*, 2022, nwac050.
- J. Liao, A. Z. Jin, A. Z. Chafe, A. Pillarisetti, T. Yu, M. Shan, X. Yang, H. Li, G. Liu and K. R. Smith, *Atmos. Environ.*, 2017, **165**, 62–72.
- E. T. Gall, E. M. Carter, M. C. Earnest and B. Stephens, *Am. J. Publ. Health*, 2013, **103**, 67–72.
- R. Ahmad, Y. G. Zhou, N. Zhao, A. Abbas, G. Li, P. Raman, C. Pemberton-Pigott, M. Sultan and R. J. Dong, *Fresenius Environ. Bull.*, 2019, **28**, 9835–9842.
- N. Bruce, P. Perez and R. Albalak, *Bull. World Health Organ.*, 2000, **78**, 1080–1092.
- Z. H. Luo, L. Zhang, G. Li, W. Du, Y. C. Chen, H. F. Cheng and S. Tao, *Atmos. Res.*, 2021, **248**, 105247.
- M. M. Pier and F. Massimo, *Int. J. Environ. Res. Publ. Health*, 2017, **14**, 1048.
- G. Yang, Y. Wang, Y. X. Zeng, G. F. Gao, X. F. Liang, M. G. Zhou, X. Wan, S. C. Yu, Y. H. Jiang, M. Naghavi, T. Vos, H. D. Wang, A. D. Lopez and C. J. L. Murray, *Lancet*, 2013, **381**, 1987–2015.
- G. Hoek, R. M. Krishnan, R. Beelen, A. Peters, B. Ostro, B. Brunekreef and J. D. Kaufman, *Environ. Health*, 2013, **12**, 43.
- J. Lissowska, A. Bardin-Mikolajczak, T. Fletcher, D. Zaridze, N. Szeszenia-Dabrowska, P. Rudnai, E. Fabianova, A. Cassidy, D. Mates, I. Holcatova, V. Vitova, V. Janout, A. Mannetje, P. Brennan and P. Boffetta, *Am. J. Epidemiol.*, 2005, **162**, 326–333.
- W. J. Seow, W. Hu, R. Vermeulen, H. D. Hosgood III, G. S. Downward, R. S. Chapman, X. He, B. A. Bassig, C. Kim, C. Wen, N. Rothman and Q. Lan, *Chin. J. Cancer*, 2014, **33**, 471–475.
- M. A. Jeuland and S. K. Pattanayak, *PLoS One*, 2012, **7**, e30338.
- G. Li, X. Bai, S. H. Huo and Z. G. Huang, *IET Renew. Power Gener.*, 2020, **14**, 959–967.
- N. Zhao, B. W. Li, D. Y. Chen, R. Ahmad, Y. Zhu, G. Li, Z. P. Yu, J. Li, E. L. Wang, S. Yun, H. Yoon, I. Yoon, Y. G. Zhou, R. J. Dong, H. Wang, J. X. Cao, J. He and X. X. Ju, *Waste Manag.*, 2020, **104**, 20–32.
- K. Jiang, B. Fu, Z. H. Luo, R. Xiong, Y. T. Men, H. Z. Shen, B. G. Li, G. F. Shen and S. Tao, *Environ. Pollut.*, 2022, **306**, 119378.
- W. S. Zhang, Z. F. Lu, Y. Xu, C. Wang, Y. F. Gu, H. Xu and D. G. Streets, *Atmos. Environ.*, 2018, **176**, 158–170.
- L. Wang, Y. Jing, Z. Pu, Z. Xiu, W. Zhe, Z. Fen, S. Jie and C. M. Chen, *Open J. Air Pollut.*, 2013, **2**, 47–55.
- H. Liu and D. I. Mauzerall, *Energy Econ.*, 2020, **90**, 104844.
- H. Wang, Y. Lei, X. Chen, J. He and L. Gao, *J. Environ. Res. Sci.*, 2015, **28**, 1510–1517.
- Y. Hao, Q. Zhang, M. Zhong and B. Li, *J. Clean. Prod.*, 2015, **108**, 944–954.



- 25 G. Li, Z. T. Lu, J. Zhang, H. Li, Y. G. Zhou, A. M. I. Zayan and Z. G. Huang, *Int. J. Agric. Biol. Eng.*, 2020, **13**, 241–246.
- 26 B. Xu and B. Lin, *J. Clean. Prod.*, 2015, **112**, 1454–1463.
- 27 J. F. Zhang and J. M. Samet, *J. Thorac. Dis.*, 2014, **7**, 3–13.
- 28 H. Li, S. Yang, J. Zhang and Y. Qian, *J. Clean. Prod.*, 2015, **112**, 1350–1359.
- 29 R. Ahmad, Y. G. Zhou, H. Li, N. Zhao, A. Abbas, M. Sultan, P. Raman and R. J. Dong, *Fresenius Environ. Bull.*, 2021, **30**, 4365–4372.
- 30 N. Zhao, B. W. Li, R. Ahmad, F. Ding, Y. G. Zhou, G. Li, A. M. I. Zayan and R. J. Dong, *Case Stud. Therm. Eng.*, 2021, **28**, 101484.
- 31 Z. G. Huang, J. Zhang, M. M. Pan, Y. H. Hao, R. C. Hu, W. B. Xiao, G. Li and T. Lyu, *Biochem. Eng. J.*, 2020, **179**, 108330.
- 32 G. Li, R. C. Hu, N. Wang, T. L. Yang, F. Z. Xu, J. L. Li, J. H. Wu, Z. G. Huang, M. M. Pan and T. Lyu, *J. Clean. Prod.*, 2022, **355**, 131768.
- 33 P. Wilkinson, K. R. Smith, M. Davies, H. Adair, B. G. Armstrong, M. Barrett, N. Bruce, A. Haines, I. Hamilton, T. Oreszczyn, I. Ridley, C. Tonne and Z. Chalabi, *Lancet*, 2009, **374**, 1917–1929.
- 34 H. Z. Shen, Z. H. Luo, R. Xiong, X. Liu, L. Zhang, Y. Li, W. Du, Y. C. Chen, H. F. Cheng, G. F. Shen and S. Tao, *Environ. Int.*, 2021, **157**, 106841.
- 35 C. Venkataraman, G. Habib, A. Eiguren, H. Miguel and K. Friedlander, *Science*, 2005, **307**, 1454–1456.
- 36 S. Ahmad and J. A. P. Oliveira, *J. Clean. Prod.*, 2015, **94**, 130–136.
- 37 N. Zhao, B. W. Li, H. Li, G. Li, R. C. Wu, Q. Hong, P. Mperejekumana, S. Liu, Y. G. Zhou, R. Ahmad, A. M. I. Zayan, C. Pemberton-Pigott and R. J. Dong, *Environ. Res.*, 2021, **94**, 110683.
- 38 H. E. S. Mestl, K. Aunan, J. Fang, H. M. Seip, J. M. Skjeltvik and H. Vennemo, *J. Clean. Prod.*, 2005, **13**, 57–70.
- 39 Q. Li, X. H. Li, J. K. Jiang, L. Duan, S. Ge, Q. Zhang, J. G. Deng, S. X. Wang and J. M. Hao, *Sci. Rep.*, 2016, **6**, 19306.
- 40 R. Ahmad, A. Abbas, W. Jufei, H. Li, M. Sultan, B. Li, S. M. Nyambura and X. J. Pan, *Environ. Sci. Pollut. Res.*, 2021, **28**, 58135–58141.
- 41 R. Ahmad, Y. G. Zhou, N. Zhao, C. Pemberton-Pigott, H. J. Annegarn, M. Sultan, R. J. Dong and X. X. Ju, *Int. J. Agric. Biol. Eng.*, 2019, **12**, 160–167.
- 42 O. Adetona, Z. Li, A. Sjödin, L. C. Romanoff, M. A. Villalobos, L. L. Needham, D. B. Hall, B. E. Cassidy and L. P. Naeher, *Environ. Int.*, 2013, **53**, 1–8.
- 43 J. Robinson, C. Pemberton-Pigott and H. Annegarn, 2018, available online: <http://www.newdawnengineering.com/website/library/Papers+Articles/SeTAR/SeTAR%20HPT%20Multistove%20comparison,%20Robinson%20et%20al%20FINAL.xlsx>.
- 44 J. Wang, H. H. Lou, F. Yang and F. Cheng, *J. Clean. Prod.*, 2016, **134**, 447–455.
- 45 L. S. Båfver, B. Leckner, C. Tullin and M. Berntsen, *Biomass Bioenergy*, 2011, **35**, 3648–3655.
- 46 M. Cui, Y. Xu, B. Yu, L. Liu, J. Li and Y. Chen, *Sci. Total Environ.*, 2022, **83**, 155529.
- 47 F. Mamuye, B. Lemma and T. Woldeamanuel, *Sustainable Environ. Res.*, 2018, **28**, 32–38.
- 48 J. Liu, D. L. Mauzerall, Q. Chen and T. Zhu, *Environ. Sci.*, 2016, **113**, 7756–7761.
- 49 J. Granderson, J. S. Sandhu, D. Vasquez, E. Ramirez and K. R. Smith, *Biomass Bioenergy*, 2009, **33**, 306–315.
- 50 J. P. McCracken and K. R. Smith, *Environ. Int.*, 1998, **24**, 739–747.
- 51 A. Edwin, T. Erika, W. Jin, S. David and M. Vijay, *Energy Sustainable Dev.*, 2010, **14**, 172–185.
- 52 D. Ludwinski, K. Moriarty and B. Wydick, *Environ. Dev. Sustain.*, 2011, **13**, 657–676.

