WHO Indoor Air Quality Guidelines: Household fuel Combustion

Review 2: Emissions of Health-Damaging Pollutants from Household Stoves

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Lead authors: those authors who contributed to one or more parts of the full review, and reviewed and commented on the entire review at various stages.

Disclaimer:
The work presented in this technical paper for the WHO indoor air quality guidelines: household fuel combustion has been carried out by the listed authors, in accordance with the procedures for evidence review meeting the requirements of the Guidelines Review Committee of the World Health Organization.

Full details of these procedures are described in the Guidelines, available at: http://www.who.int/indoorair/guidelines/hhfc ; these include declarations by the authors that they have no actual or potential competing financial interests. The review was conducted in order to inform the development of recommendations by the Guidelines Development Group. The authors alone are responsible for the views expressed in this publication, which do not necessarily represent the views, decisions, or policies of the WHO.

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Summary

Background

Emissions testing for solid-fuel household stoves used for cooking or space heating have been conducted under controlled settings performing water boiling tests or simulated cooking tasks. There is limited evidence to date that these tests reflect the emissions seen in actual homes during normal daily cooking activities, and little consensus on appropriate duration and protocols for field testing. For these emissions data to be useful for comparison to emissions limits used in conjunction with air quality guidelines, there needs to be consensus on what tests are comparable and which measurements should be compared to emissions limits.

Objectives and key questions

The aim of this review was to assess the levels of emission of health damaging pollutants released from household combustion technologies. The following key questions were defined:

1. What are the levels of emission of health damaging pollutants from household solid fuel burning stoves in both laboratory and field tests, to be used as a basis for modelling indoor air concentrations
2. What are the implications of differences between laboratory and field emission results?

Methods

We performed a systematic review of studies reporting data on emissions of particulate matter (PM), carbon monoxide (CO) and other health-damaging pollutants from household stoves and fuels. Our sources included Science Direct, Web of Science and Google Scholar, and contact with subject experts. The findings are presented separately for laboratory and field based emissions testing and results from these two methods are compared.

Findings

Although emissions measurements of household cookstoves have been conducted since the early 1990's, there are still very limited numbers of emission measurements from cookstoves in the field during normal daily cooking activities, and generalizations over large geographical regions are limited by our understanding of the factors that drive the variability in emissions over geographic scales. A better understanding of the variability of emissions over geographical areas is critical to a better understanding of the health and climate impacts of cookstoves on a global scale.

There are also limited in-field emissions measurements from stoves used for space heating and a lack of protocols for use in laboratory tests. The literature has focused on wood burning cookstoves, and there are still a large number of gaps in the cookstoves and fuels for which there are in-field emissions testing data, especially for low-emission/advanced stoves, but also for charcoal stoves, coal stoves, and the wide range of agricultural residues that are burnt in cookstoves across the world. Thus field-based emissions during normal daily cooking activities are not well quantified, and further testing work is a priority.

In the data that are available, the limited number of direct comparisons between laboratory and field measurements using consistent methodology indicates that current laboratory tests are not representative of the emission concentrations or the range of particle properties and composition that are seen in the field.

Conclusions

Development of approaches to link laboratory and field testing are critical to the development of cookstoves that meet both programmatic and user expectations when deployed in real homes.

1. Introduction

1.1. Household stoves and the focus of this review

There are many types of household stoves for cooking and heating across the world. The major health impacts from household cookstoves, however, are experienced disproportionately in the developing world from solid fuel stoves, mainly biomass and coal, often in remote rural areas or urban slums. There is also increasing concern about the pollution from solid fuels, particularly wood, in household space-heating stoves and fireplaces in industrialized nations. In the US, for example, new residential wood heaters are governed by 40 CFR Part 60 Subpart AAA (1988) where emissions testing is required at an EPA-accredited laboratory to certify that each wood stove model line complies with particulate emission limits. Similar standards apply in European countries, Australia, Chile, and other temperate countries. Since these stoves are directly vented to the outside and thus not strictly an issue for indoor air quality, they are not addressed in detail in this review.

In contrast, there have been relatively few national regulations and associated official measurement procedures around the world related to indoor emissions from the types of cookstoves used by nearly half of the world's households, which often are unvented. Similarly, only relatively recently has the performance been characterized of the various types of cleaner cookstoves and fuels that are being developed and promoted. This review thus focuses on what is known about the emissions and other important performance characteristics of both traditional and newer solid-fuel cookstoves, emphasizing their influence on indoor air quality.

Many constituents in stove emissions are known to be hazardous to human health and impact climate, but in practice emissions measurements largely focus on a subset of these; those that are important markers for health endpoints (respirable particles[1], carbon monoxide, SO_2), and those that are important to estimate climate impacts (CO_2, CO, CH_4, non-methane hydrocarbons, N_2O, and the mixtures of elemental (black[2]) and organic carbon in fine particulate matter). There are many organic species emitted from stoves that have health impacts, including some specific toxic contaminants such as dioxins and furans *(1)*, and each of the organic species emitted has an individual climate impact. Since information on detailed organic speciation of household stove emissions is very limited, especially in field during daily cooking activities, in this review we focus on the principal health-and climate related pollutants listed above that are typically monitored during emissions measurements.

1.2. Relevance of emissions to indoor air quality standards

Indoor air pollution in households with stoves using solid fuels is typically composed of direct emissions from the stove into indoor environments, whether fugitive emissions during refueling

[1] Although the precise term is aerosols to include both airborne solid and liquid forms, we keep to the simpler terms, particles and particulate matter.
[2] Although commonly referred to as black carbon, there are a number of different definitions and measurements methods for black carbon, so here we refer to the more precise chemical description of elemental carbon.

or from leaks in the case of stoves with chimneys or flues, or emissions from unvented stoves into indoor environments, combined with the fraction of the emission that penetrates the home from the outdoor environment (along with emissions from surrounding homes). The degree to which indoor emissions and penetration of ambient emissions contribute to exposures of an individual will depend on whether the stove is located indoors or in the courtyard, if indoor stoves have a flue or not, the time that individuals spend in different rooms in the home and other environments, the ventilation rate and volume of the home, the proximity of the home to other households and other sources, and the direct and fugitive emissions from their stove. Although this review focuses on emissions, we acknowledge that the relationships to exposures depend on the location of the stove and whether it has a flue combined with the behaviors of the people in the home, which prevents making direct health inferences based on comparison of emissions across stove types.

Common with other devices, testing is easiest to do in simulated cooking settings under controlled conditions, for example in a room adjacent to a laboratory. Emission rates and emission properties, however, are affected by a range of other factors in real households that are difficult to reproduce in simulated settings, such as the variety of fuel types, combinations, sizes and composition including moisture content that are used in homes. In addition the "use cycle", or the cycle of cooking tasks in homes is difficult to compare to standardized procedures in simulated settings used to standardize tests so that one fuel/stove combination can be compared to another. Combined with other factors that affect emission rates and properties such as varying skill, patience, and experience of the cook, the type of pots, and environmental conditions, among others, inevitably no simple lab cooking cycle, such as the most commonly used Water Boiling Test, (WBT) represents the actual cooking done in any population over time. Although tests under controlled conditions have the advantage of minimizing the impact of all other factors on the tests to focus on the fuel/stove combination, below we present evidence from the literature that they often do not represent the actual performance or emission properties of fuel/stove combinations in households, even just after installation let alone after stove deterioration sets in.

Assessment of emissions has often included a wider variety of compounds and particulate species than are typically measured in indoor air pollution studies, personal exposure studies or epidemiologic investigations, where PM and/or CO are most commonly measured as markers for the mixture of other compounds present. In part this is because emissions studies generally include additional climate-related parameters being measured, but it also reflects that the majority of emission studies have been performed in simulated kitchens/laboratories where additional instrumentation is logistically more feasible than in real homes, which may be in remote locations. Emissions measurements in laboratories can be conducted with more sophisticated methods that those used in the field, and play an important role during technology development to determine whether a particular cookstove is likely to achieve indoor air quality goals. Thus approaches to link laboratory-based tests and field-testing results are a priority.

Stove emissions also have indirect health impacts from long distance transport of primary emissions in the atmosphere, and chemical transformation of precursors into secondary particulate and other health-damaging species in the atmosphere. For respirable particulate matter, the specific toxicity of particles, and thus the health impact, may also be affected by chemical transformation as the particles are transported in the atmosphere. Indirect impacts also include potential health impacts as a result of climatic change caused by pollutants. Although the potential for these widespread impacts is recognised *(2)*, in the current review we focus on primary emissions from cookstoves in and around homes. The health impacts from potential climatic change, formation of secondary particles and aging of particles in the atmosphere are not addressed here. The effects of cookstove emissions on climate, climate-related health impacts and carbon trading are covered in more detail in Review 11 (Costs and financing). More detailed reviews on health-damaging pollutants specific to biomass stoves are in Review 4 (Health risks from household air pollution), and for coal stoves in Review 8 (Coal).

1.3. Physical processes affecting emissions

Solid fuel combustion in cookstoves emits a complex mixture of particulate and gaseous species, many of which are known health-damaging pollutants. Some of these pollutants contribute to levels of commonly regulated pollutants in the ambient environment (defined as "criteria" pollutants in the US Clean Air Act): respirable particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x) and sulphur oxides (SO_x), or contribute to ozone formation in the atmosphere. Gas phase pollutants include compounds that are carcinogenic (benzene, formaldehyde), probably carcinogenic (1,3-butadiene), and possibly carcinogenic (styrene) to humans *(3)*. Cookstoves also emit both gas and particulate phase polyaromatic hydrocarbons and oxygenated polycyclic aromatic hydrocarbons *(4)* that may mediate health impacts via the formation of proteins and DNA adducts, the depletion of glutathione, and generation of reactive oxygen species (ROS) to enhance oxidative stress *(4-7)*. Many biomass fuels and coal also contain low concentrations of chlorine that lead to low level emissions of dioxins and furans *(1, 8)*. Unlike biomass, many coals also contain intrinsic contaminants such as sulphur, arsenic, silica, fluorine, lead, mercury, which are not destroyed during combustion, but released into the air in their original or oxidized form (see Review 8 for more detailed description of health impacts from coal emissions).

The combustion literature focusing on industrial sources, e.g. *(9-12)* sheds light on the formation mechanisms present in cookstoves, though the magnitude of emissions, and in many cases the relative contribution of each mechanism, are different. Emissions from combustion fall into several major categories:

1. Complete combustion products – non-toxic CO_2 and water vapor are the only emissions when combustion is 100% complete in fuels that have few intrinsic contaminants, such as most biomass.
2. Products of incomplete combustion (PIC) – a wide range of carbon-containing compounds created because combustion is rarely complete in small combustion devices, such as simple cookstoves. By mass, these are dominated by CO, but thousands of more complex compounds are also created, many of which exist partially or fully in the particulate phase along with elemental carbon particulate matter (commonly referred to as soot).
3. Nitrogen oxides created by fixing nitrogen from the air, which is normally only important at higher combustion temperatures.
4. Pollutants created from contaminants in the fuel, such as sulphur and nitrogen oxides, airborne particles from fuel ash, mineral fibers and gaseous Hg.

Direct emissions from the stove may also lead to formation of secondary pollutants created in the atmosphere downwind from the stove due to chemical changes of the emitted pollutant precursors – examples are sulphates, organic particles, and ozone. As our focus is indoor air quality, we emphasize the processes and fuel characteristics that affect complete combustion (1 and 2, above) and result in emissions of PICs, which are most relevant for most solid-fuel cookstoves, although mineral fibers and fuel-borne contaminants (4 above) may be important in health impacts from burning raw coal.

1.3.1 Combustion processes

Combustion of biomass, coal, or liquid fuels proceeds through a sequence of steps, and many of the key pollutants are formed when that sequence is disrupted *(13)*. First, fuel enters the vapor phase, through either simple evaporation (for liquid fuels) or pyrolysis/devolatilization processes (for solid fuels such as coal and biomass). In the vapor phase, combustion occurs in a flame or distributed reaction zone, where highly reactive radicals successively attack fuel molecules and the fuel-like intermediates formed from them. Fuel molecules are broken down into smaller molecules and typically proceed through carbon monoxide to eventually form carbon dioxide. In the case of solid fuels, there is an additional, parallel process (char burnout) in which surface reactions oxidize the carbon and hydrogen remaining in the devolatilized solid (char). For complete combustion to occur, the fuel must have adequate residence time at a sufficiently high temperature, in the presence of oxygen.

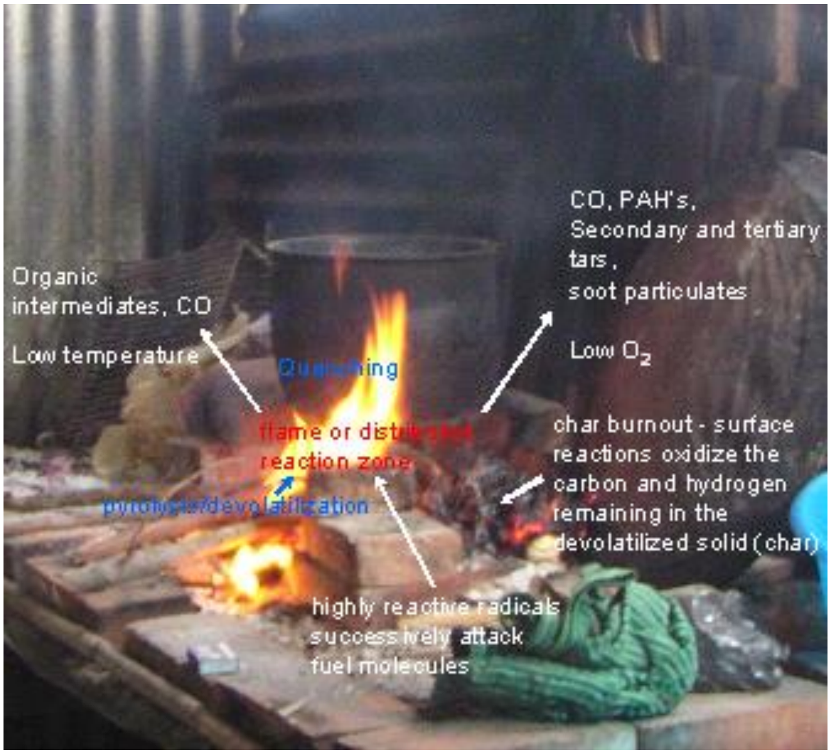
> In household-scale combustion devices, the combustion sequence can be disrupted by quenching or poor mixing, leading to the escape intact from the combustion zone of PICs : hydrocarbons, CO, and PAH's, as well as part of PM (

Figure **1**). Where cold surfaces interact with combustion gases, combustion reactions are quenched, resulting in emissions of combustion intermediates. Depending on where in the process quenching occurs, these intermediates can be fuel molecules, hydrocarbon and oxygenated hydrocarbon intermediates, CO, PAHs, or PM. Peak combustion temperatures influence the mix of partial combustion products produced, with lower temperatures favoring primary tars and oxygenated PAHs in biomass combustion systems *(9)*.

In cookstoves, quenching and thus pollutant formation can readily occur where hot gases impinge on the surface of the cooking pot unless adequate reaction time has been provided to complete combustion upstream of the surface. Poor mixing of air with fuel gases also contributes to the emission of several of these pollutants. Where mixing is inadequate, it is possible to produce hot, but locally fuel-rich regions. Sudden release of volatiles can also produce temporary oxygen-starved hot regions. In these regions, fuel molecules react unimolecularly or with other fuel molecules, forming soot precursors such as acetylene, butadiene, aromatic hydrocarbons, and PAHs. PAHs can nucleate to form solid soot particles, a major constituent of PM. Depending on the degree of oxygen starvation, the reaction may proceed to CO rather than to soot and soot precursors.

Many of these compounds eventually come in contact with air and burn further downstream in the cookstove, but some may escape. Combustion of solid and liquid fuels invariably involves some fuel-rich regions, but cookstove design can promote air/fuel gas mixing, for instance through swirling flows or turbulence due to fan-driven air flow. In addition, simply increasing the size of the fire tends to reduce PIC emissions by allowing longer residence times *(14)*, such as larger institutional cookstoves in schools and restaurants. Some space heating stoves are also designed to burn hot large fires for short periods and capture the heat in masonry for release over the night, which results in lower emissions per unit output.

Figure 1: Incomplete combustion processes in household stoves



Conversion of atmospheric N_2 to NO occurs most readily at high temperatures, and this "thermal" mechanism contributes to NO levels from gas and kerosene cookstoves, for example *(15)*. However, for most coal combustion conditions *(12)*, and for biomass under the moderate-temperature conditions common in residential combustion *(16)*, most NO emissions are due to fuel nitrogen released during both devolatilization and char combustion stages *(10, 12)*.

1.3.2 Fuel characteristics

Fuel type and quality influence pollutant emissions in several ways: fuels differ in the peak temperatures achieved and the relative importance of gas-phase vs condensed phase reactions. Furthermore, solid fuels, especially biomass, may be moist, leading to greater likelihood of inefficient, low-temperature combustion zones. Fuels also differ in the levels of contaminants they contain. Of the fuels commonly used in household combustion, coal has the highest levels of ash, sulphur and nitrogen, while kerosene has negligible levels of all heteroatoms except sulphur. Biomass spans a large range of nitrogen and ash levels, with herbaceous biomass (e.g. corn stover, grasses) overlapping coal's range, and woody biomass containing lower levels. Biomass sulphur levels are lower than that of coal, and typically comparable to those for developed-world kerosene *(15, 17, 18)*. Sulphur content of kerosene in the developing world is not well characterized and seems to vary widely *(15)*. Sulphur, once it enters the vapor phase, is effectively converted to oxides (SO_x), which form particulates directly or through atmospheric reactions, or which condense on existing particles as the combustion products cool and mix into ambient air, but not near the stove indoors *(11)*. SO_x emission levels can be correlated with fuel sulphur levels and with effectiveness of volatilization of S, which increases with the temperatures to which the solid fuel is exposed. Minerals too partition between vapor and solid phases, with more volatile minerals such as potassium reacting, vaporizing, and forming fine "fly ash" particles *(11)*. Reactions among inorganic species influence the volatilization and condensation conditions of the mineral compounds. This process, like the one forming SO_x, occurs more readily at high temperatures. Thus the composition of the ash from solid fuels varies considerably, but in general household stoves do not create the flue-gas velocities needed to suspend a high proportion of fuel ash. LPG and natural gas have very small amounts of ash or other contaminants, but can burn at high temperatures to produce nitrogen oxides.

The situation is further complicated from an emissions and health perspective by the burning of household trash and other refuse in household stoves. The overall health implications of these activities are hard to characterize, however, due to the highly variable nature of the specific trash items burnt. Although the specific emission mixture will depend on the polymers present, a number of studies have reported emissions of irritating gases and aerosols during the thermal decomposition of polymers *(19)*, and combustion products of PVC exposure have been shown to cause respiratory irritation and death in animal models *(20, 21)*. These studies have largely focused on inhalation exposures as a result of building fires, however, and the health implications in human populations of burning of plastics along with other solid fuels in cookstoves are unclear.

1.3.3 Interaction of fuel type and combustion processes

Fuel type can influence the propensity of stoves to emit products of incomplete combustion (PICs).

- Gaseous and liquid fuels are much easier to burn nearly completely because they allow greater control over fuel/air mixing. Gaseous or vaporized liquid fuels can be premixed with air, eliminating the possibility of oxygen-starved regions *(22)*. Some kerosene stoves and lamps, however, use wicks *(23)* rather than pressurized fuel delivery systems *(24)*, which leads to uneven fuel-air mixing and greater PIC emissions.
- For solid fuels, reducing fuel size can reduce PIC emissions. Reducing the size of the fuel pieces, makes complete combustion occur more quickly *(25)*, because of reduced resistance both to heat transfer and to oxygen diffusion. Most advanced combustion stoves, whether incorporating a fan or not, only work well for smaller fuel pieces and are often designed with small openings to discourage users from loading with large pieces. Biomass pellets and coal briquettes are also options for achieving small, uniform particles.

1.4. Other household level sources of emissions

Although the focus of this review is on cookstove emissions, other household sources of emissions contribute to elevated air pollutant concentrations indoors and in neighbourhoods. In large areas of the world stoves are not only used for cooking, but also provide space heating during cold seasons. This has several important ramifications for indoor air quality guidelines;

1. Although frequently grouped with cookstoves, the patterns of use and refuelling of these stoves are distinct.
2. The areas of the house that have the highest air pollutant concentrations indoors may shift between seasons. For example winter heating may result in higher concentrations in living areas compared to kitchens as a result of coal space heating *(26)*.
3. The specific composition of the particles may vary according to the different fuels used on a seasonal basis.

In Chinese homes in Hubei and Shaanxi, 70% of homes that used space heating and 43% of homes that did not use space heating in the winter reported changing their main cooking fuel type between seasons predominantly from biomass or agricultural residues in the summer to coal in the winter *(26)*. In contrast, in many homes in peri-urban areas around Ulaanbaatar, Mongolia the majority of cooking is done using electric appliances in combination with raw coal heating stoves. Thus while the cooking appliances have little or no combustion emissions, the homes still have highly polluted indoor air during winter seasons *(27)*. In addition to space heating stoves, households may also use a stove for income generating household industries (such as tortilla making in Michoacán, Mexico), which can result in extended use of the stove and additional burdens of indoor air pollution *(28)*. Similarly, where electrification is not widespread, use of kerosene lamps may also result in significant additional burdens of indoor air pollution *(15)*. Finally small-scale industries conducted inside or in the immediate surroundings of households (metal working, pottery making, candy making etc.) and trash burning may result in locally elevated pollution concentrations that result in elevated indoor air pollution levels.

2. Key questions and review methods

2.1. Key questions

The aim of this review was to assess the levels of emission of health damaging pollutants released from household combustion technologies. The following key questions were defined:

1. What are the levels of emission of health damaging pollutants from household solid fuel burning stoves in both laboratory and field tests, to be used as a basis for modelling indoor air concentrations
2. What are the implications of differences between laboratory and field emission results?

2.2. Review methods

Sources of information

In addition to searching the available literature and previous global inventories, members of the research community, solicited via email, contributed pre- and unpublished manuscripts (papers and reports) as additional information sources.

Search methods and terms

Literature searches combined the results of three search engines: Google Scholar, Web of Science, and Science Direct, in order to compile cookstove emission data for the current inventory. The search was restricted to papers written in the English language and covered the period from January 1997 to April 2013. From every search, which included the terms *cookstove, (stove) emissions, emission factor, Controlled Cooking Test, stove performance (test)*, and *Water Boiling Test*. The top 200 search results in the search output were evaluated for inclusion.

Information extraction

Studies that included original primary emissions measurements of either traditional and/or improved cookstove measurements in the developing world were eligible for inclusion in the inventory. Although relevant from a human health standpoint, studies that solely report indoor air quality were excluded as they are covered elsewhere in the report. Information was not restricted to peer-reviewed material as there are a number of reports not publicly available that contain valuable emissions data, and the overall number of peer-reviewed resources with primary measurement data is limited.

2.3. Assessment of study quality

Papers were rated as either of 'high' or 'medium' quality, based on the following criteria:

High quality:

- If the authors clearly documented the protocol used,
- Reported the results of multiple measurements in order to describe if any variation existed.
- Measurement campaign had IWA compatible results.

Medium quality:

- Known protocol, unknown number of tests.
- Cooking procedure is not clearly described.
- Clearly laid out protocol, no repeats.
- No reported statistics

Examples of these assessments are provided in the table summarising individual studies, in Annexes 2(a) and 3.

3. Current status of emissions measurements from household cookstoves

3.1. Issues in categorizing stove and fuel types

There are a large and diverse number of cookstove designs around the world, used in a number of different environmental conditions, with fuels that differ by location. Grouping these cookstoves into categories is therefore challenging, and there are a number of different ways it can be approached, which can be loosely grouped under structural approaches or emissions-based approaches. Since one of the purposes of this review is to characterise how current technologies and interventions perform in relation to indoor air quality guidelines, we have chosen a structural approach where the range of emissions for each category of stove can be presented and compared to emission rates that would meet the WHO air quality guidelines (AQG), see Review 3 (Emissions model). Figure 2 shows the classification scheme for stoves and fuels used in this review, which is based on a more extensive classification presented in Annex 4.

Figure 2: Classification scheme for stoves and fuels

Fuels		Energy Efficiency		Ventilation		Combustion Chamber		Materials		
Type	Category	Improved	Unimproved	Unvented	Vented	Natural Draft	Forced Draft	Local	Manufactured	Advanced

Fuel Type	Biomass	Coal	Liquid	Gas	Solar	Electricity
Fuel Category	• Trunk wood • Branches/twings • Pellets • Briquettes • Dung • Crop residue/sawdust • Charcoal	• Lignite • Briquettes • Other coal	• Kerosene • Ethanol, methanol	• LPG, NG • Biogas • Dimethyl ether		

This classification scheme cannot encompass all of the wide diversity of stoves, but this approach forms a structural basis for grouping stove types, and captures the main types of improved stove being disseminated. For traditional stoves, however, there is less information available[3].

3.2. Issues in standardizing measurement protocols

Comparison of results from laboratory tests is hampered by a range of variations in testing procedures, with little ability to relate the results from different variations. There are variations in the testing procedures between authors, even when using the same published protocols for each test related to test procedures (water volumes, simmering temperatures, treatment of evaporative losses etc.), fuel preparation (e.g. timed feeding of precision cut blocks of fuel vs naturally sources branches and twigs), analytical methods, and dilution approaches for particulate samples. Similarly for field based measurements the tests are of varying durations, choosing individual meals or daily cooking events, using different sampling probes, instruments and protocols. Since there is currently no way to adjust for these variations in test procedure, even less to adjust for operator variability which is known to strongly impact emissions, we have grouped the results without applying any correction factors.

3.3. Laboratory based emissions measurements (WBT)

The largest emissions data sets found were for controlled tests conducted in simulated cooking situations, most commonly employing a version of the Water Boiling Test (WBT) for standardization (see Annex 1. Stove testing protocols for a description of the WBT and other

[3] For a more detailed picture of stoves by geographical location the following references give a more nuanced view of stove types

- Global Alliance for Clean Cookstoves - http://www.cleancookstoves.org/our-work/the-solutions/cookstove-technology.html
- Indian improved stoves - a compendium - http://www.fao.org/docrep/006/AD585E/ad585e00.pdf
- Chinese fuel saving stoves - a compendium - http://www.fao.org/docrep/006/ad586e/ad586e00.htm

stove testing protocols)[4] Measured in these tests were both parameters related to emissions from the stove, such as grams of pollutant per kg of fuel, as well as parameters related to the fuel efficiency of the stove, such as grams of fuel per MJ of energy delivered to the pot. This is because there are two important internal efficiencies of a stove for our purposes:

- Combustion efficiency (CE) – how much of the chemical energy in the fuel is converted to radiant energy and heat, and
- Heat transfer efficiency (HTE) – how much of the released energy is absorbed into the pot or cooking process.

Box 1: Combustion and heat transfer efficiency

Combustion Efficiency

In practice, it is difficult to measure CE directly and so typically a surrogate called Nominal Combustion Efficiency (NCE) is used, defined as $cCO_2/(cCO_2+cCO+cCH_4+cTNMHC+cTSP)$ *(29, 30)*. A more abbreviated term based on modeling of emissions *(31)* called the Modified Combustion Efficiency (MCE) defined as the emissions of $cCO_2/(cCO_2 + cCO)$ on a molar basis, is frequently used due to the ease of measurement *(32) (33)*. As CO makes up the most PIC mass, by far, this is considered a reasonable estimate of the percent of fuel carbon that has been converted to CO_2, i.e., the degree of complete combustion.

Heat Transfer Efficiency

In practice, HTE is also difficult to measure directly. Thus, usually, it is calculated as the overall fuel efficiency measured by the WBT divided by the NCE – see footnote 3. Perhaps it should thus be termed Nominal HTE, but this is rarely done.

Multiplied together, these estimate the overall stove fuel thermal efficiency (OTE), at least for the particular set of cooking tasks represented by the WBT.

Equation 1 OTE = f(CE x HTE)

A stove may reach lower emissions overall by either increasing CE or HTE, or both Significant improvement in CE from simple traditional stoves is required to reach the low emissions levels that are needed for major reductions in health effects, although improvements in HTE can help. Combustion efficiency and emissions, however, are not entirely a function of either a particular stove or fuel, but a fuel/stove combination and the way they are operated. Kerosene emissions are quite different between wick and pressurized stoves, for example. And the same biomass stove will have different characteristics when used with wood compared to dung. In general, however, the variation in emissions across stoves trends according to physical form of the fuel: solid> liquid>gaseous.

Table 1 shows emission factors (g/kg dry fuel) based on laboratory testing for a range of stove and fuel combinations taken from the available literature *(33)*. Further details on the included studies are presented in Annex 2(a), and emission factors expressed as g/MJ of energy

[4] Here, as is customary, we refer to these as laboratory tests although they are not usually done in laboratories *per se*, but rather in combustion facilities or field stations where hoods and dilution systems have been built.

delivered to the pot for the same stove and fuel combinations are presented in Annex 2(b). These are the two most important metrics for evaluating fuel/stove combinations from an air pollution standpoint. While g/MJ of energy delivered to the pot provides useful information on heat transfer characteristics in laboratory tests during stove development, and normalizes emissions by energy delivered (as fuel density and moisture content varies across fuels) in the field this parameter is hard to measure and requires many assumptions about the specific quantities and energy required to cook individual food items in the pot. From an atmospheric standpoint g/kg dry fuel gives useful information that can be combined with national statistics and surveys on fuel use to evaluate the overall mass of pollutants entering the atmosphere from household solid fuel combustion.

Table 1: Average emission factors for household stoves for laboratory or simulated kitchen measurements using the WBT[5]

Fuel	Stove classification		Emission factors (g/kg)							References
			CO_2	CO	CH_4	TNMOC	PM	BC	NCE	
Wood	Traditional Unvented	Local	1610	52.8	8.9	8.5	2.5		85.86	*(34) (30, 33, 35-44)*
			(2700-1320) 38	(136.0-11.0) 44	(29.5-1.58) 35	(22.4-0.08) 33	(4.6-0.83) 15		(93.55-70.7) 48	
	Traditional Vented	Local	1560	23.6	0.6	0.1	1.5		97.26	*(43)*
			(1560) 1	(23.6) 1	(0.6) 1	(0.1) 1	(1.5) 1		(97.26) 1	
	Improved Unvented	Natural	1580	42.4	8.8	9.0	2.3	1.556		*(30, 33-36, 39, 40, 42, 44-47)*
			(2031-1171.9) 39	(139.1-10.8) 64	(14-1.51) 35	(10.97-0.92) 29	(12.88-0.09) 38	(2.145-1.14) 4		
	Improved Vented	Local	1592	48.8	2.8	1.6	3.5			*(34, 38, 44, 45)*
			(1926.25-1392) 4	(81.66-16.33) 5	(5.466-0.36) 4	(1.595) 1	(3.4676) 1			
Dung	Traditional Unvented	Local	1000.5	42.99	11.63		2.45			*(40, 42)*
			(1027-974) 2	(61.39-18) 3	(17.56-5.7) 2		(4.6-0.55) 3			
	Improved Unvented	Local	1056	24.6	3.4		3.4			*(40, 42)*
			(1065-1046) 2	(31.62-14) 5	(3.58-3.25) 2		(4.9-1.645) 5			
Crop Residue	Traditional Vented	Local	2005	68.7	6.2	3.2	3.2		92.39	*(40)*
			(2510-1500) 2	(70.7-66.6) 2	(10.3-2.1) 2	(3.5-2.9) 2	(4.7-1.7) 2		(93.48-91.29) 2	
	Improved Vented	Natural	1582	133.7	4.5	9.0	11.0		78.30	*(43, 44)*
			(2130-959) 4	(179.0-70.39) 4	(8.97-0.86) 4	(17.966-2.53) 4	(18-4.02) 2		(85.9-70.7) 4	
Charcoal	Traditional Unvented	Local	2559	162.3	6.9	10.3	2.12			*(36, 44-46)*
			(3026-2091) 6	(284.52-34.2) 7	(7.8-5.60) 5	(15.47-6.5) 5	(4.13-0.12) 2			
	Improved	Natural	2622	198.5	6.6	8.6	1.77			*(33, 35, 36, 40, 44-*

[5] The values in parentheses are the maximum and the minimum average emissions factor for the stoves measured. No weighting was applied for the number of repeats for each stove type. The number after the parentheses indicates the number of stoves for which emissions data were compiled. TNMOC - Total non-methane organic compounds on a carbon basis normalized to methane. Although most studies report either TSP or $PM_{2.5}$, they are combined as 99% by mass are less than 1 µm.

			Emission factors (g/kg)							References
Fuel	**Stove classification**		**CO_2**	**CO**	**CH_4**	**TNMOC**	**PM**	**BC**	**NCE**	
	Unvented									*46)*
			(3074-2155) 18	(390.4-19.86) 21	(10.8-2.279) 17	(13.4-4.8) 16	(5.83-0.1) 5			
Charcoal Briquette	Traditional Unvented	Local		9.0			4.8			*(41-43)*
				1			1			
Lignite	Traditional Unvented	Metal	1940	66.9	3.3	1.3	4.4		93.28	*(43)*
			(2380-1500) 2	(68.4-65.3) 2	(3.5-3.2) 2	(2.4-0.2) 2	(8.7-0.1) 2		(93.43-93.13) 2	
	Traditional Vented	Brick	1677	83.0	3.7	1.3	6.6		91.28	*(43)*
			(2550-1060) 3	(95.0-66.2) 3	(6.1-0) 3	(2.0-0.5) 3	(14.2-1.6) 3		(93.69-88.96) 3	
Briquettes	Traditional Unvented	Metal	1881	71.5	0.02	9.36	1.80		97.00	*(41, 43)*
			(2550-1568) 5	(104.5-19.9) 5	(0.02-0.01) 2	(17.6-0.02) 5	(3.4-0.322) 5		(98.04-95.9) 5	
	Traditional Vented	Metal	2220	31.0	1.19		0.19		97.10	*(43)*
			(3060-1380) 2	(43.3-18.7) 2	(2.09-0.28) 2		(0.217-0.171) 2		(97.7-96.4) 2	
	Improved Unvented	Metal	1160	40.3	1.60	0.005	0.48		96.60	*(43)*
			1	1	1	1	1		1	
Kerosene	Traditional Unvented	Local	3180	27.2	0.48	0.34	0.29		99.54	*(40, 43, 45)*
			(3714-2943) 5	(62.1-2.31) 5	(1.071-0.009) 4	(0.415-0.295) 2	(0.701-0.025) 5		(99.57-99.52) 4	
LPG	Improved Unvented	Gas burner	2532	14.2	0.04	3.7	0.35		98.98	*(40, 43)*
			(3120-1390) 3	(19.1-8.7) 3	(0.05-0.012) 3	(4.1-3.3) 2	(0.52-0.01) 3		(99.43-98.53) 3	
NG	Improved Unvented	Gas burner	3440	0.3	0.04	0.13	0.16		99.99	*(43)*
			(3440) 2	1	1	(0.17-0.09) 2	(0.20-0.11) 2		(99.99) 2	
Coal Gas	Improved Unvented	Gas burner								

3.4. Field based emissions measurements

3.4.1 Controlled cooking tests

Average emission factors during controlled cooking tests are presented for different stove and fuel combinations below, Table 2. Emissions have been measured in very few controlled cooking tests. The data, however, are important in that they have most often been performed in direct comparison with other tests, such as the water boiling test and during normal daily cooking activities. No maximum and minimum average emissions factor for the stoves are reported as results for only one stove of each type were reported.

Table 2: Emission factors for household stoves using controlled cooking tests (CCT)

					Emission factors (g/kg fuel)							
Fuel		**Stove classification**		**Stoves**	**CO_2**	**CO**	**CH_4**	**TNMOC**	**PM**	**BC**	**NCE**	**References**
Biomass-	Wood	Improved Unvented	Natural	1		47.00			5.00			*(48)*
	Charcoal	Improved Unvented	Local	1	2543	273.2	14.3	29.9	14.1		81.2	*(37)*
Liquid	Kerosene	Improved Unvented	Natural	1	2948	92.5	1.0	13.3	0.7		94.2	

3.4.2 Normal daily cooking activities

An increasing number of emission tests during normal daily cooking activities have been performed. The tests vary in duration from a single meal event to a single day of cooking activity. Average emission factors (g/kg dry fuel) are presented for different stove and fuel combinations below, Table 3. The values in parentheses are the maximum and the minimum average emissions factor amongst the different studies where the stove type was measured. No weighting was applied for the number of repeats for each stove type. The number after the parentheses indicates the number of stoves for which emissions data were compiled.

Table 3: In field emission factors for household stoves during daily cooking activities

Fuel		Stove classification		Emission factors (g/kg fuel) CO_2	CO	CH_4	TNMOC	PM	BC	NCE	References
Biomass-	Wood	Traditional Unvented	Local	1509	87.2	5.0	10.0	7.4	0.7	93.4	*(30, 38, 48-50)*
				(1672-1267) 6	(145-25.66) 12	(7.4-2.8) 5	(14.85-2.4) 4	(11.7-5) 11	(0.7-0.6) 3	(94-93) 19	
		Improved Unvented	Local	1711	74.5			3.3	1.4	93.4	*(30, 48, 49, 51)*
				(1711) 1	(77-72) 2			(5.9-1.2) 6	(2.145-0.8) 5	(93.4) 6	
			Natural	1672	74.5	5.1	3.9	4.8	1.5	93.3	*(30, 48, 49, 51)*
				(1711-1633) 2	(88.6-47) 10	1.0	1.0	(13.3-1.2) 14	(2.145-0.8) 6	(93.4-93.1) 14	
			Forced	1661	50.0	3.4	8.2	1.9	0.1	95.5	*(49)*
				1	1	1	1	1	1	1	
		Improved Vented	Local	1628	40.9	2.5		5.6		93.4	*(38, 50)*
				(1764-1452) 4	(65.33-16.33) 5	(4.4-0.93) 4		1.0		1	
	Charcoal	Improved Unvented	Local	2469	311.9	14.7	41.7	15.0		78.4	*(37)*
				(2543-2394) 2	(350.5-273.2) 2	(15.0-14.3) 2	(53.4-29.9) 2	(15.9-14.1) 2		(81.2-75.6) 5	
Liquid-	Kerosene	Improved Unvented	Local		11.0				90		*(52)*
					1.0				1		
Gas-	LPG/NG	Improved Unvented	Gas burner								

3.5. Differences between field and laboratory results

Although the relative merits of laboratory and field tests are frequently debated, both are important in evaluating emissions from cookstoves, and provide complimentary information critical to the development and dissemination of cookstoves. Laboratory tests (which here also refer to tests in simulated kitchens) are able to use constant flow hoods and dilution tunnels combined with scales on which the stove sits to measure fuel consumption as the burn test progresses. In addition laboratory based measurements allow the use of measurement equipment whose sensitivity, size, power requirements and noise levels currently preclude their use in real homes, but provide important information on the emissions characteristics of the stoves. Such tests provide levels of precision in emissions factors that are currently not feasible in real homes during normal daily activities, as installation of large vented hoods in homes is impractical, and may well impact operator behavior. Added to this, the remote locations of many of the communities, irregular power supply for equipment, and complicated logistics for travel and shipping of samples make field measurements difficult to perform. Thus, there are a range of emissions parameters that are currently not feasible to measure in real homes during daily cooking activities. The disadvantages of laboratory tests, however, are that it is not currently possible to reliably link the results to cookstove performance in the field, as the available evidence points to systematic differences in the results that are discussed further below. Indeed it is not currently possible to link the three different phases (cold start, hot start and simmer) of the water boiling test (WBT), most commonly used to evaluate cookstove performance in the laboratory, into a meaningful synthesis of overall performance *(28)*.

Field tests of emissions using sampling probes in homes have been shown to have good agreement in modified combustion efficiencies compared with constant flow sampling hoods under field conditions *(48)*, and emission ratios of gaseous species to CO_2 when sampling directly from a flue have been shown not to be different to those from a hood placed over the entire stove and flue *(29)*. Thus, field assessments using probes, though still logistically difficult, may be conducted more readily than installing hoods for developing realistic combustion profiles, and have the advantage that they monitor emissions from the stove during actual daily cooking and heating activities. Field tests of emissions are therefore more representative of the actual usage and impacts of the stove for health impacts, and for global inventories for climate related endpoints.

Still lacking, however, are longitudinal assessments of emissions as most assessments measure a single meal, or single day in small numbers of individual homes. It remains a challenge to recruit statistically representative samples in areas where multiple fuel types of varying composition are used, which vary by season. Emissions and their composition are also highly dependent on operator behaviour and cooking activities, and the resulting combustion *(50)*, as stoves are fundamentally not a steady state system, but a batch process *(53)*. Added to this, in many areas stove and fuel stacking during the day or between seasons make choice of representative sampling durations a challenge. For example, Johnson et al found that women in Mali used multiple types of cookstoves during the day, and the factors that impacted cooking energy use were the type of cookstove application (six meal types and 5 non-meal applications), family size, total mass of wet and dry ingredients, mass of dry ingredients, the use of burning embers as an igniter, and the number of fires used during a cooking event *(54)*.

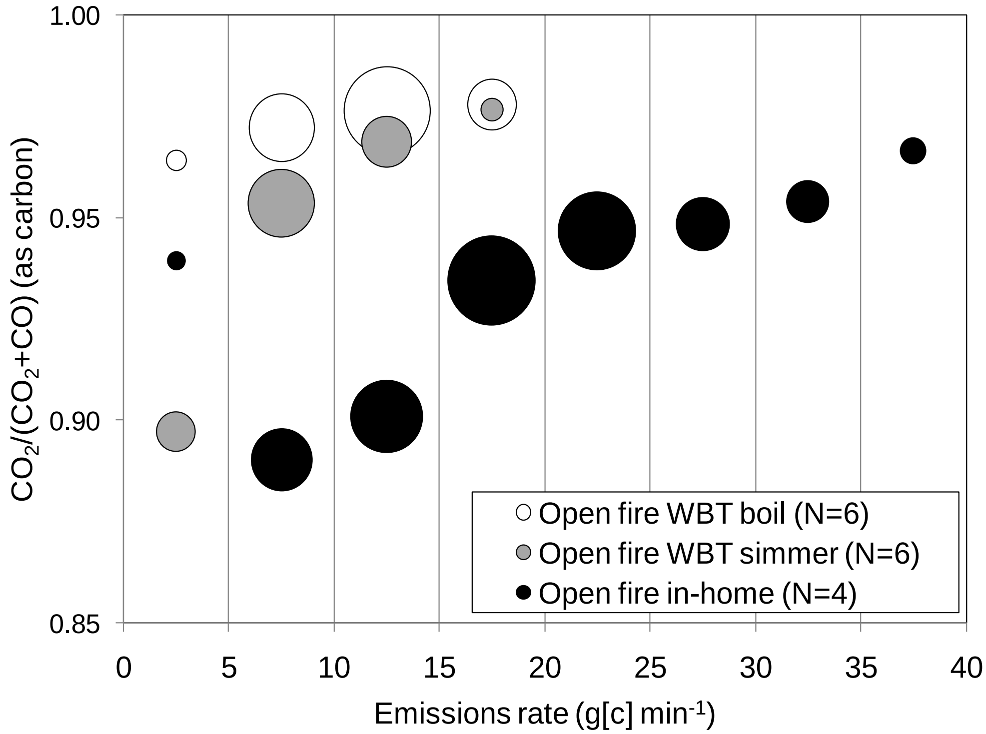
3.6. Comparisons among laboratory, simulated kitchen, and field measurements

Stove performance tests in laboratories or simulated kitchens are based on the assumption that performing a standard task such as boiling water or cooking a staple food produces representative estimates of efficiency and emissions. While there is tendency to want to use laboratory-based tests to evaluate potential impacts of improved stoves, due to the limited number of in field emissions measurements, there have simply not been enough direct comparisons performed to date to determine if current laboratory stove tests are representative of what happens in real homes during normal stove use. The available evidence, however, consistently points to current controlled laboratory tests not being representative of actual homes during daily cooking activities. Both the Controlled Cooking Test (CCT) and the Water Boiling Test (WBT) have been demonstrated not to reflect emissions during normal cooking activities *(28, 34, 37, 48, 55)*. Moreover, the bias of these tests does not seem to be systematic between stove types and therefore cannot currently be adjusted for using simple correction factors. Perhaps more importantly, a common misconception is that the controlled test is a good enough representation of daily cooking tasks because it involves cooking a staple food (e.g. cooking rice), even though cooking involves many more tasks than the one in the test. Although variability both within and between tests has been shown to be greater in homes during normal cooking activities when compared to controlled cooking tests (between 9% to 43% increase in coefficients of variation for CO_2 and CO emission rates between in-home and WBT samples *(48, 50)*), the following 2 examples demonstrate, however, that controlled tests are fundamentally different from cooking that occurs in real homes both in terms of combustion and emissions of particulate species.

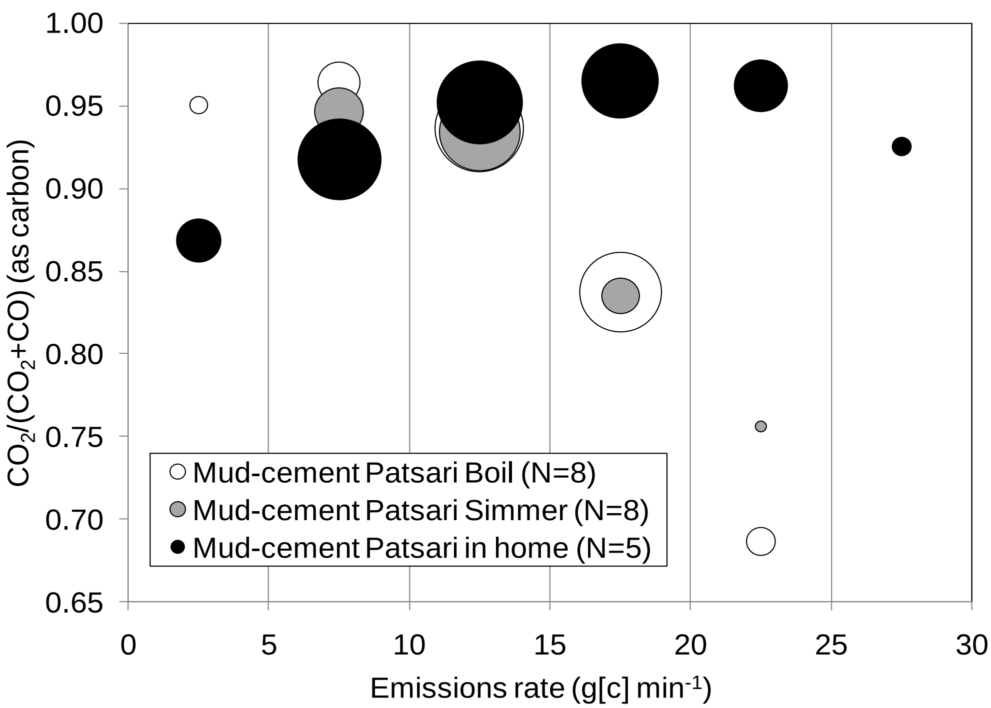
Figure 3 shows carbon emission rates (x-axis) plotted against modified combustion efficiency MCE (y-axis), with the size of each bubble representing the respective fraction of carbon emitted, for both open fires and improved Patsari stoves in Michoacan, Mexico *(32)*. For the open fire emissions rates greater than 20 gC min^{-1} were not evident during the different WBTs, though they accounted for 49% of all carbon emissions for in-home samples, indicating WBTs did not replicate the high emission rates found during normal stove use. In addition the MCE values at lower emissions rates were considerably greater for the WBT than those seen in homes, indicating more complete combustion in the lab tests than in in-home use. Simmering phases of WBTs were also not indicative of in-home MCE values.

Figure 3. Emission profiles of open fires (A) and mud-cement Patsaris (B) during WBTs and normal stove use in homes *(32)*. Reproduced with permission

A



B

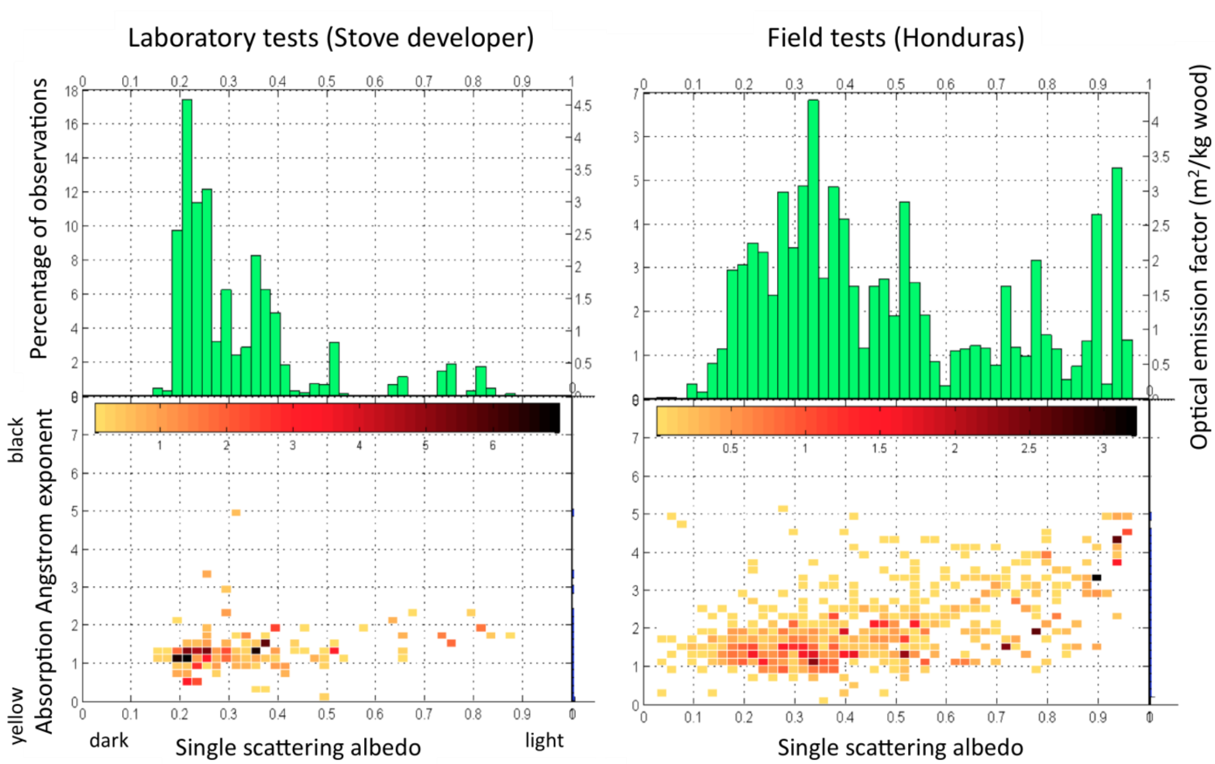


Note: Size of bubble represents fraction of total carbon emitted during in-home or WBT emissions sampling. Total carbon for the WBT was determined as the combined carbon for both boiling and simmering phases.

For the Patsari stove the WBT was also not representative as during in-use testing, the stove maintained a much higher MCE at higher emissions rates. Thus for both stoves the distribution of emissions rates by MCE were systematically different indicating that the laboratory test protocol did not represent in-field stove activity or emissions.

Although the above conclusion is based on relatively small sample sizes, similar results have also been observed independently by other investigators. Figure 4 also shows that for particulate emissions there are systematic differences in the properties of the particles between the laboratory and the field (absorption and color in this case, but indicating a difference in the organic fractions and composition). Although currently the implications of the differences of these particulate properties for health are currently not known, these are evidence of different results between laboratory and field, and that the laboratory is missing a large fraction of the particulate emission *(56)*. Thus, standardized laboratory data produce mainly black particles at lower emission rates, and in-field measurements produce greater emissions of particles that contain a less-absorbing, yellow component.

Figure 4. "Fingerprints" using real-time data compare laboratory (left) and field testing (right) emissions. Reproduced with permission



Note: Bottom graph: Joint frequency plot of a color measure (Absorption Angstrom exponent) and a darkness measure (single scattering albedo). Colors indicate percentage of 2-minute observations. Top graph: Marginal frequency plots showing prevalence of dark particles in emissions. Left axis is percentage, right axis is scaled to total emissions *(56)*.

Fuel saving estimates based on controlled tests have also proved misleading as fuel consumption during daily cooking activities in KPTs was not represented by either WBTs or CCTs *(28, 34)*. Similar differences between controlled testing results and performance in real homes in India resulted in misplaced expectations and dissatisfaction with national programs

(57). Unless burn cycles can be demonstrated to represent what happens in real homes, controlled laboratory tests are liable to produce results that are biased to different extents depending on stove type. Since both laboratory and field tests of emissions both play an important role in stove development to ensure indoor air quality guidelines will be met, there is a clear need to develop metrics that allow the performance in laboratory and field tests to be compared.

3.7. Multiple devices and fuel stacking in the field.

In many rural areas of China, it is common to find multiple stoves, including some improved varieties, and multiple solid fuels present in the same kitchen, which are used for different tasks *(26, 58)*. Similarly in many areas where LPG stoves are available, 'fuel and/or stove stacking' can occur where traditional stoves are used in conjunction with cleaner stoves *(26, 28)* . In these instances the emissions, indoor air quality and pollutant composition will reflect the fuels/appliances being used to accomplish the different tasks. Since the exposure patterns induced by these stove arrangements are likely different, the impacts of the emissions from stoves in each of these categories for indoor air or for health endpoints will also differ. In addition, corresponding shifts in the particle size distribution complicate relationships between exposures to particulate mass and corresponding health impacts *(59)*. Currently, there is little information on the effect of stove stacking on total emission per home, and emissions related parameters for each stove that depend on the specific set of tasks being performed as emissions measurements in laboratories or in the field mainly focus on individual stove types, and systematic investigations of the impact of multiple fuel use on in field emissions are not currently available.

3.8. Variability in emissions measurements, sample sizes and metrics

The physical factors governing emissions from combustion vary on spatial scales of a few millimeters over short temporal scales, which are difficult to observe in laboratory settings and not feasible to observe during in-home combustion. Many of the physical factors governing emissions are controlled by user behavior, including choices about ignition, fire feeding, wood size, fuels used for special purposes, types of food cooked, or inclusion of wastes as fuels. User behavior, while highly individual, is governed regionally by common customs, which can be captured by sufficiently large sample size. Current emissions inventories are based on a very limited number of repeat tests (typically 3) of individual stove types in controlled tests *(29, 30, 60)*. Although there are an increasing number of in-field assessments of emissions and indoor air quality, there is still very limited information on the variability of emissions by different stove types over different geographical regions. As a result we have only tentative estimations of sample sizes that are required for robust inventories.

Based on measurements of 25 traditional stoves in El Salvador *(61)* and 8 in Mexico *(48)* over a single season in each locality, figure 5 shows the reduction in the margin of error of the 95% confidence interval (95% CI) with increasing sample size, using the definition of the margin of error as the value added or subtracted from the sample mean which determines the length of the interval, expressed as a percentage of the mean. The figure indicates that with measured variability in emissions factors, larger sample sizes of homes than have previously been collected are required for robust estimates of emission factors. Large reductions in the margin of error are achieved with sample sizes of 15-20 independent measures with reduced benefits thereafter given costs of sampling additional homes.

Figure 5. Reduction in the margin of error of the 95% CI with increasing sample size for emission measurements

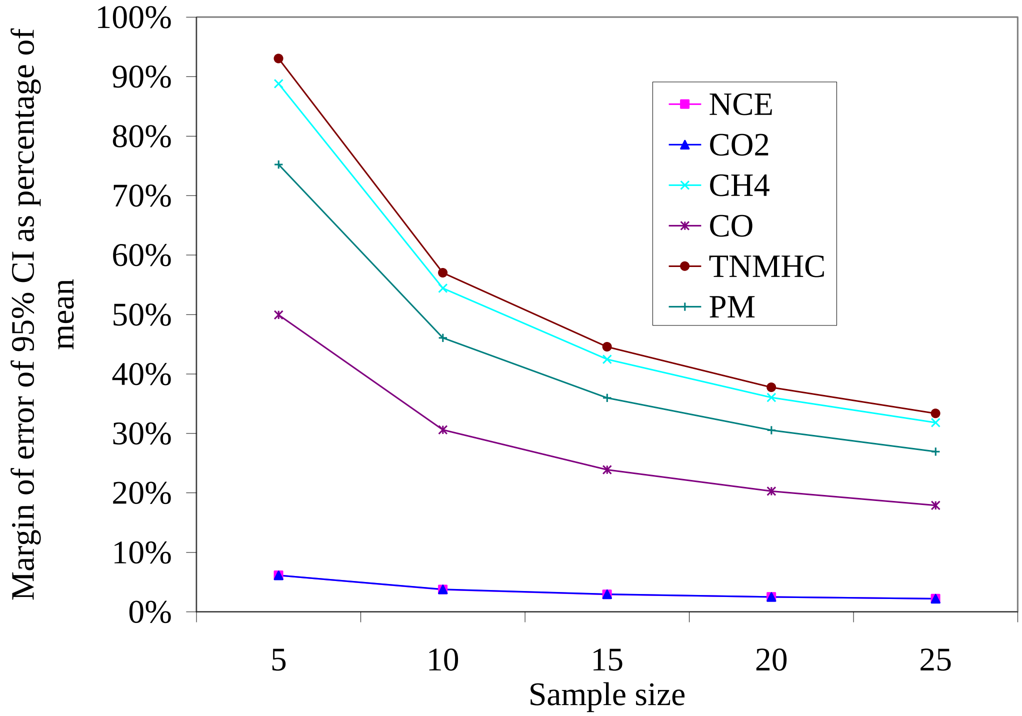


Figure 5 suggests that sample sizes on the order of 15-20 households would give a good estimate of stove emissions for communities in a particular location. It is not clear, however, how large the geographical area these could represent, due to the lack of data on spatial variability of emissions, and the primary factors that drive differences in emissions for a specific stove type over geographical areas. While ongoing work aims to answer some of these issues, generalizations over large geographical regions are limited by our understanding of the factors that drive the variability in emissions.

4. Discussion and assessment of overall quality of evidence

GRADE domains were used to guide assessment of the quality of evidence available on laboratory and field emissions.

Nature of evidence available

The data available from the majority of studies of stove and fuel emissions include important pollutants which are health-damaging, which were obtained from range of different types of test, the majority conducted in laboratory settings (including simulated kitchens), rather than in homes during normal cooking tasks. There is a wide range of types of solid fuel stoves and fuels; this variability together with variation between studies in how test protocols have been applied, led to a decision not to carry out meta-analysis.

Study design (testing protocols)

Three main test protocols have been used, the water boiling test (WBT), controlled cooking test (CCT) and the kitchen performance test (KPT), with most data available from the first two. For the laboratory-based studies, all results are presented for the WBT which increases comparability, but even so there are variations between studies in the way this has been applied (see risk of bias). The largest, well-standardized set of studies have been reported from the USEPA stove laboratory, but so far these have been restricted to solid fuel stoves burning wood. For field studies during 'normal cooking activities' measurement periods ranged from a single cooking event to all cooking in a single day.

Risk of bias

For emission rate measurements, the two main sources of bias lie with (i) the test protocol used, and (ii) the manner in which this protocol was applied in practice, along with quality control procedures. All results for laboratory-based tests are for the WBT, those reported by the USEPA for wood burning stoves are well standardized and quality controlled, for others it is recognized that there are variations in respect of test procedures (water volumes, simmering temperatures, treatment of evaporative losses etc.), fuel preparation (e.g. timed feeding of precision cut blocks of fuel vs. naturally sources branches and twigs), analytical methods, and dilution approaches. Overall, the laboratory-based data has much lower intrinsic risk of bias than the field studies, but as discussed further below, there is evidence that laboratory and field testing are not comparable.

Indirectness

The objective of this review is to summarize values for emissions of health-damaging pollutants, and therefore no indirectness is present.

Heterogeneity

For all pollutants there was a wide range of values for the most commonly tested stove/fuel subgroups (traditional and improved unvented wood stoves, improved charcoal stoves). Formal testing of statistical heterogeneity was not conducted in light of the concerns about methodological variations between studies.

Precision

As noted, the largest number of studies is available for laboratory studies, for which precision is good for common types of traditional and improved wood-burning stoves, but rather poorer for other types of solid fuel stoves, kerosene and gas. For field studies, precision is moderate for wood-burning solid fuel stoves, but poor for other groups.

Publication bias

Given the heterogeneity of methods used to apply the test protocols between studies, and the large number of stove/fuel subgroups, formal testing of publication bias has not been carried out. While the series of wood-burning stove tests reported by USEPA represent a complete series, and unpublished sources were included in the systematic review to minimize this bias, it is quite possible that there is other unpublished material with different results.

Comparison of laboratory and field testing

Assessment of studies comparing features of emissions from test protocol-based and 'normal use' studies provided evidence that the WBT and CCT do not reflect well emissions during normal cooking activities, in two ways, namely variability and nature of emissions. More specifically, there is greater variability within and between homes, the coefficient of variation being between 9% and 43% higher for CO_2 and CO with normal use activities. Furthermore, the WBT and CCT have been found to be fundamentally different from normal cooking, both in terms of emission rates for a given level of combustion efficiency, and also in terms of the composition of particles emitted (although the health implications of the latter are not known). These findings highlight the need for enhanced methods for, and attention given to, testing of emissions in normal use, although it remains the case that emission rates from traditional unvented stoves tend to be substantially higher in normal use than in laboratory-based protocol defined tests.

Summary

Findings were assessed as of **moderate quality** for the laboratory evidence, and of **low quality** for the field evidence. This highlights the need for more extensive measurement of emissions in situations reflecting more closely 'real life' usage, and with protocols which are better adapted to this purpose

5. Conclusions

The main sources of data on laboratory testing (e.g. USEPA) provide reliable, high quality evidence, using standard protocols for the tests that are widely published and disseminated. Although common protocols for the tests are used, there are still significant variations that are possible between groups related to test procedures (water volumes, simmering temperatures, treatment of evaporative losses etc.), fuel preparation (e.g. timed feeding of precision cut blocks of fuel vs naturally sources branches and twigs), analytical methods, and dilution approaches. The reliability of the results, however, is generally higher than field measures, as more sophisticated approaches to the measurements of the emissions species can be used.

There is relatively limited data on field emissions and generalizations over large geographical regions are limited by our understanding of the factors that drive the variability in emissions over geographic scales.

There is good evidence from independent researchers doing direct comparisons between the laboratory and the field that the laboratory tests are not representative of the emission concentrations or the range of particle properties and composition that are seen in the field. Ways to link laboratory and field testing should be prioritized, including adjusting testing protocols to reduce the length of the test to enable more repeats, reducing the focus placed on boiling water fast, evaluating potential approaches to weight the proportion of high power and low power tasks to match community behavior *(28)*, or other approaches to match burn cycles during normal daily cooking activity *(32)*, or generation of performance curves *(62)*.

There are still a large number of gaps in the stoves and fuels for which there are in field emissions testing data, especially on low-emission/advanced stoves, but also for charcoal and coal stoves, so field-based emissions during normal daily cooking activities are not well quantified, and further testing work is a priority.

Emissions from LPG stoves throughout the world are poorly characterized and there is concern that some perform substantially worse than better quality burners in industrialized nations, which needs to be investigated.

Annex 1. Stove testing protocols

Common testing protocols[6][7]		
Water boiling test (version 4.1.2)	**Controlled cooking test**	**Kitchen performance test**
Three phases, a cold start followed by a hot start and a 45 minute simmer using 5 or 2.5 liters of room temperature water Designed to give information primarily on time to boil and overall thermal efficiency	Stoves are compared as they perform a standard cooking task, typically rice or legumes, but tortillas and other foods may also be prepared Intended to be closer to the actual cooking that local people do every day than water boiling	Measures fuel consumption over a successive 3-7 day period during normal daily cooking activities. Principal field–based procedure to demonstrate the effect of stove interventions on household fuel consumption,
Other testing protocols		
Prasad[8] *(63)*	**Johnson[9] *(32)***	**Uncontrolled cooking test[10] *(62)***
Burn 1 kg of wood, or enough to last an hour, divided into 5-6 equal parts charged over intervals into the stove. Weigh the water before and after to generate performance curves of thermal efficiency	Similar to Prasad, but real-time instruments are used to replicate the distribution of emission rates and combustion efficiencies seen during daily cooking activities in homes.	The cook prepares a meal how they want, with the only measurements being that of the firewood used and the final mass of food cooked. Reports specific fuel consumption (total energy consumed [MJ] to cooked food mass [kg]), and fuel burn rate (total energy used [MJ] to cooking time [min]

[6] See PICA http://www.pciaonline.org/testing
[7] See HEH Stove performance protocols http://ehs.sph.berkeley.edu/hem/?page_id=38

Annex 2. Emission results and studies included in laboratory or simulated kitchen measurements

(a) Studies included for emission factors for household stoves for laboratory or simulated kitchen measurements using the WBT

Area	Region	Stove classification	Primary Fuel	Total n. of entries	Protocol used	Repeats*		Species measured	Quality assess ment	Source	Institution	Institution type	Year
						WBT	UCT						
USA/ Canada	USA	Improved Vented, Improved Unvented, Traditional Unvented	Wood	4	WBT	4		CO, PM	Medium	Report	Aprovecho Research Group	NGO	2007
Africa	South Africa	Traditional Unvented, Improved Unvented	Wood	5	WBT	30		CO, PM	High	Peer-Review Journal	University of Whitwatersra nd	University	1996
Asia	Thailand	Traditional Unvented, Improved Unvented	Wood/ Charcoal	24	WBT	72		CO_2, CO, CH_4, TNMOC	High	Peer-Review Journal	Asian Institute of Technology	University	2002
Asia	Thailand	Traditional Unvented, Improved Unvented	Wood/ Charcoal	33	WBT	165		CO_2, CO, CH_4, TNMOC	High	Peer-Review Journal	Asian Institute of Technology	University	2002
Asia	China	Improved Vented	Coal	2	WBT	9		OM, PM, BC	High	Peer-review Journal	China Academy of Sciences	University	2006
Asia	China	Improved Vented	Coal	2	WBT			OM, PM, BC	Medium	Peer-review Journal	China Academy of Sciences	University	2005
Asia	India	Traditional Unvented, Improved Unvented	3Wood/ 1Gas/ 1Liquid	5	WBT	16		$PM_{2.5}$	High	Peer-review journal	Indian Institute of Technology Bombay	University	2008
USA/ Canada	United States	Traditional Unvented, Improved Unvented	11Wood/ 2Charcoal/ 1Biomass	14	WBT	42		CO_2, CO, $PM_{2.5}$	High	Peer-review Journal	U.S. EPA	Government	2009

Area	Region	Stove classification	Primary Fuel	Total n. of entries	Protocol used	Repeats*		Species measured	Quality assessment	Source	Institution	Institution type	Year
						WBT	UCT						
USA/ Canada	USA	Improved Vented, Improved Unvented, Traditional Unvented	Wood	4	WBT	4		CO, PM	Medium	Report	Aprovecho Research Group	NGO	2007
Africa	South Africa	Traditional Unvented, Improved Unvented	Wood	5	WBT	30		CO, PM	High	Peer-Review Journal	University of Whitwatersrand	University	1996
USA/ Canada	United States	Traditional Unvented, Improved Unvented, Improved Vented	20Wood/ 14Charcoal/ 6Crop Residue	44	WBT	132		$PM_{2.5}$, CO_2, CO, CH_4, TNMOC	High	Presentation	U.S. EPA	Government	2011
Asia	Thailand	Traditional Unvented, Improved Unvented	10Wood/ 1Crop Residue/ 1Coal	12				PM	Medium	Peer-review journal	Asian Institute of Technology	University	2005
Asia	China	Improved Unvented	Wood/ Crop Residue	9	WBT			$PM_{2.5}$, CO	High	Peer-review journal	Tsinghua University	University	2007
USA/Canada	USA	Traditional Unvented, Improved Unvented	1Charcoal/ 4Wood	5	WBT	15		OM	High	Peer-review journal	Aprovecho Research Center	NGO	2008
USA/Canada	United States	Traditional Unvented, Improved Unvented, Improved Vented	31Wood/ 4Charcoal/ 1Ethanol/ 1Kerosene/ 1LPG	38	WBT	114		PM, CO	High	Peer-review Journal	Aprovecho Research Center	NGO	2010
USA/Canada	United States	Traditional Unvented, Improved Unvented	1Wood	2	WBT	3		PM, CO	Medium	Report	Aprovecho Research Center	NGO	2008

Area	Region	Stove classification	Primary Fuel	Total n. of entries	Protocol used	Repeats*		Species measured	Quality assessment	Source	Institution	Institution type	Year
						WBT	UCT						
USA/ Canada	USA	Improved Vented, Improved Unvented, Traditional Unvented	Wood	4	WBT	4		CO, PM	Medium	Report	Aprovecho Research Group	NGO	2007
Africa	South Africa	Traditional Unvented, Improved Unvented	Wood	5	WBT	30		CO, PM	High	Peer-Review Journal	University of Whitwatersrand	University	1996
Asia	Thailand	Improved Unvented	1Charcoal/ 1Coal	2	WBT	9		PM	High	Peer-review journal	Asian Institute of Technology	University	1999
Asia	India	Traditional Unvented, Improved Unvented	1Biogas/ 1Briquette/1Charcoal/ 6Crop residue/ 4Dung/ 2Kerosene/ 3Root/1LPG/ 9Wood	28	WBT	84		PM, CO_2, CO, CH_4	High	Report	University of California, Berkeley	University	2000
USA/ Canada	United States	Traditional Unvented, Improved Unvented	4Charcoal/ 2Wood	6	WBT	6		PM, CO	High	Report	Aprovecho Research Center	NGO	2006
USA/ Canada	United States	Traditional Unvented	15Coal/ 1Wood	16	WBT	48		PM, CO_2, CO, TNMOC	High	Peer-review Journal	University of California, Berkeley	University	2008
Asia	India	Traditional Unvented, Improved Unvented	2Biomass/ 4Dung/ 4Wood	10	WBT	40		PM, CO	High	Peer-review journal	IIT Bombay	University	2001
Asia	China	Improved Unvented	3Wood/ 9Charcoal	12	WBT	12		CO_2, CO, CH_4, TNMOC	High	Peer-review journal	Tsinghua University	University	2009

Area	Region	Stove classification	Primary Fuel	Total n. of entries	Protocol used	Repeats*		Species measured	Quality assessment	Source	Institution	Institution type	Year
						WBT	UCT						
USA/ Canada	USA	Improved Vented, Improved Unvented, Traditional Unvented	Wood	4	WBT	4		CO, PM	Medium	Report	Aprovecho Research Group	NGO	2007
Africa	South Africa	Traditional Unvented, Improved Unvented	Wood	5	WBT	30		CO, PM	High	Peer-Review Journal	University of Whitwatersrand	University	1996
Asia	China	Traditional Unvented, Improved Unvented, Improved Vented, Traditional Vented	11Coal/ 1Coalgas/ 4Cropresidue /2Kerosene/2 LPG/ 2Natural Gas/ 6Wood	28	WBT	84		PM, CO_2, CO, CH_4, TNMOC	High	Peer-review journal	Rutgers University	University	2000
Latin America	Mexico	Improved Vented, Improved Unvented	8Wood	8	UCT/ WBT	30	21	CO_2, CO, CH_4	High	Peer-review journal	University of California, Irvine	University	2008
USA/ Canada/ Latin America	USA/ Honduras	Traditional Unvented, Improved Unvented	21Wood	21	UCT/ WBT	13	45	OM, PM, CO	Medium	Peer-review journal	University of Illinois, Urbana-Champaign	University	2009

b) Emission factors for household stoves for laboratory or simulated kitchen measurements using the WBT (g/MJ delivered to pot)

			Emission Factors (g/MJ-del)							
	Stove classification		CO_2	CO	CH_4	TNMOC	PM	BC	NCE	References
Wood	Traditional Unvented	Local	577	19.5	3.4	3.0	1.2			*(33, 35, 36, 40, 43-45)*
			(1785.12-87.42) 37	(66.422-0.4214) 38	(13.089-0.0896) 35	(10.44-0.027) 32	(3.09-0.107) 9			
	Traditional Vented	Local	206	3.1	0.1	0.019	0.2			*(43, 64)*
			1	1	1	1	1			
	Improved Unvented	Natural	398	11.7	2.6	2.2	0.5			*(33, 35, 36, 40, 44, 45)*
			(584.61-98.02) 32	(41.24-0.75) 35	(3.69-0.78) 30	(3.29-1.05) 24	(0.98-0.05) 10			
	Improved Vented	Local	108	1.1	0.0	0.1				*(44)*
			1	1	1	1	1			
Dung	Traditional Unvented	Local	969.53	36.6	11.68		0.96			*(40, 42)*
			(1010-929) 2	(63.66-1.303) 3	(18.209-5.16) 2		(1.99-0.33) 3			
	Improved Unvented	Local	800	10.3	2.6		0.8			*(40, 42)*
			(905.6-695) 2	(25.77-1.24) 5	(2.76-2.37) 2		(1.4-0.35) 5			
Crop Residue	Traditional Vented	Local	978	32.9	3.1	1.5	1.6			*(43)*
			(1302.7-653.6) 2	(36.69-29.02) 2	(5.34-0.90) 2	(1.82-1.28) 2	(2.45-0.73) 2			
	Improved Vented	Natural	644	61.3	1.4	2.0	6.0			*(43, 44)*
			(1941-91.69) 4	(151.3-4.12) 4	(4.15-0.13) 4	(4.45-0.35) 4	(8.34-3.66) 2			
Charcoal	Traditional Unvented	Local	382	19.5	1.2	1.3				*(36, 44, 45)*
			(696-102.1) 5	(50-5.8) 5	(2.23-0.19) 5	(2.42-0.44) 5				
	Improved Unvented	Natural	245	17.0	0.8	0.7	0.53			*(36, 40, 44, 45, 51)*
			(535.66-83.73) 17	(61.12-6) 17	(2.12-0.08) 17	(1.53-0.22) 16	1			
Charcoal Briquettes	Traditional Unvented	Local		0.7		0.37				*(42)*
				1		1				
Lignite	Traditional Unvented	metal	573	21.3	1.0	0.3	0.9			*(43)*
			(651.24-494.19) 2	(28.35-14.02) 2	(1.37-0.72) 2	(0.5-0.07) 2	(1.81-0.058) 2			
	Traditional Vented	brick	364	17.6	0.8	0.3	1.4			*(43)*
			(577.98-208.1) 3	(20.44-15) 3	(1.195-0.004) 3	(0.39-0.11) 3	(2.787-0.344) 3			
Briquettes	Traditional Unvented	metal	439	8.5	0.003	0.01	0.03			*(43)*
			(567.04-311.26) 2	(13.1-3.87) 2	(0.004-0.002) 2	(0.018-0.005) 2	(0.06-0.006) 2			
	Traditional Vented	metal	679	11.1	0.45	(0.0007	0.07			*(43)*
			(811.3-547.12) 2	(17.167-4.95) 2	(0.83-0.075) 2	(0.0014-0.0001) 2	(0.086-0.045) 2			
	Improved Unvented	metal	137	4.8	0.19	0.001	0.06			*(43)*
			1	1	1	1	1			

	Stove classification		Emission Factors (g/MJ-del)							References
			CO_2	CO	CH_4	TNMOC	PM	BC	NCE	
Kerosene	Traditional Unvented	Local	137	1.1	0.02	0.02	0.01			*(40, 43, 45)*
LPG	Improved Unvented	gas burner	(157.95-84.1) 5	(3.064-0.118) 5	(0.05-0.0005) 4	(0.021-0.014) 2	(0.034-0.0005) 5			
			112	0.6	0.0015	0.175	0.015			*(40, 43)*
NG	Improved Unvented	gas burner	(142.25-67.33) 3	(0.925-0.396) 3	(0.002-0.0006) 3	(0.2-0.15) 2	(0.0239-0.0005) 3			
			117.5	0.0095	0.0013	0.0045	0.0055			*(43)*
Coal Gas	Improved Unvented	gas burner	(124.9-110.1) 2	1	1	(0.006-0.0028) 2	(0.0074-0.0036) 2			

Annex 3: Studies included in household stove emission factors reported for CCT and field emission measurements

Area	Region	Stove classification	Primary Fuel	Total n. of entries	Protocols used	Repeats			Species measured	Quality assessment	Source	Institution	Institution type	Year
						WBT	CCT	UCT						
Africa	Zambia	Traditional Unvented		2	UCT			4	CO_2, CO, TNMOC	Medium	Peer-review journal	University of Montana, Missoula	University	2003
Africa/ Asia	Uganda/ Nepal/ India	Traditional Unvented, Improved Unvented,	5Wood/ 1Pellet	6	UCT			102	OM, PM, BC, CO_2, CO, CH_4, TNMOC	High	Conference Proceedings	Berkeley Air Monitoring Group	Private Research Group	2012
Africa	Kenya	Improved Unvented	2Charcoal	2	CCT/ UCT		12	4	PM, CO_2, CO, CH_4, TNMOC	High	Presentation	University of California, Irvine	University	2009
Asia	India	Traditional Unvented, Improved Unvented,	2Wood	2	CCT		30		PM, $PM_{2.5}$, CO	High	Peer-Review Journal	Berkeley Air Monitoring Group	Private Research Group	2011
Asia	China	Improved Unvented	8 Crop residue/ 4Wood	12	WBT	30			OM, PM, BC	High	Peer-Review Journal	Tsinghua University	University	2009
Latin America	Honduras	Traditional Unvented, Improved Unvented, Improved Vented, Traditional Vented	12Wood	12	CCT		12		OM, PM, CO	High	Peer-review journal	University of Illinois Urbana-Champaign	University	2006

Annex 4: Matrix of stove designs

Fuels		**Unimproved energy efficiency technologies (unvented)**		**Unimproved energy efficiency technologies (vented)**		**Improved energy efficiency technologies (unvented)**					**Improved energy efficiency technologies (vented)**				
Bio mass	Dung	Open fire	U shaped mud	Open fire	U shaped mud	Fired clay/ ceramic	Rocket type		Adv. natural draft	Adv. forced draft	Rocket type	Fired clay /ceramic	Fixed high thermal mass	Adv. natural draft	Adv. forced draft
	Agricultural residues	Open fire	U shaped mud	Open fire	U shaped mud	Fired clay/ ceramic	Rocket type	Biochar Stoves	Adv. natural draft	Adv. forced draft	Rocket type	Fired clay/ ceramic	Fixed high thermal mass	Adv. natural draft	Adv. forced draft
	Agricultural residue pellets					Fired clay/ ceramic	Rocket type	Biochar Stoves	Adv. natural draft	Adv. forced draft	Batch feed	Cont. feed		Adv. natural draft	Adv. forced draft
	Wood	Open fire	U shaped mud	Open fire	U shaped mud	Fired clay/ ceramic	Rocket type		Adv. natural draft	Adv. forced draft	Rocket type	Fired clay /ceramic	Fixed high thermal mass	Adv. natural draft	Adv. forced draft
	Sawdust					Fired clay/ ceramic	Rocket type	Biochar Stoves	Adv. natural draft	Adv. forced draft	Batch feed	Cont. feed		Adv. natural draft	Adv. forced draft
	Wood pellets					Fired clay/ ceramic	Rocket type	Biochar Stoves	Adv. natural draft	Adv. forced draft	Batch feed	Cont. feed		Adv. natural draft	Adv. forced draft
	Charcoal	Metal stove	Clay stove	Metal stove		Fired clay/ ceramic	Rice cooker		Adv. natural draft	Adv. forced draft	metal stove	Fired clay /ceramic	Fixed high thermal mass	Adv. natural draft	Adv. forced draft
	Charcoal briquettes			Metal stove		Fired clay/ ceramic	Rice cooker		Adv. natural draft	Adv. forced draft	metal stove	Fired clay /ceramic	Fixed high thermal mass	Adv. natural draft	Adv. forced draft

Fuels		**Unimproved energy efficiency technologies (unvented)**		**Unimproved energy efficiency technologies (vented)**		**Improved energy efficiency technologies (unvented)**			**Improved energy efficiency technologies (vented)**				
Coal	Lignite	Metal stove	Floor/ bed heating (Kang)	Metal stove with heating wall		Forced draft	Down draft	Cross draft	Fixed high thermal mass	Down draft	Cross draft	Adv. forced draft	Metal stove with heating wall
	bituminous	Metal stove	Floor/ bed heating (Kang)	Metal stove with heating wall	metal stove	Forced draft	Down draft	Cross draft	Fixed high thermal mass	Down draft	Cross draft	Forced draft	Metal stove with heating wall
	anthracite	Metal stove	Floor/ bed heating (Kang)	Metal stove with heating wall	metal stove	Forced draft	Down draft	Cross draft	Fixed high thermal mass	Down draft	Cross draft	Forced draft	Metal stove with heating wall
	briquettes (lignite)	Metal stove	Floor/ bed heating (Kang)	Metal stove with heating wall	metal stove	Forced draft	Down draft	Cross draft	Fixed high thermal mass	Down draft	Cross draft	Forced draft	Metal stove with heating wall
	Honey comb briquettes (lignite)	Metal stove	Floor/ bed heating (Kang)	Metal stove with heating wall	metal stove	Forced draft	Down draft	Cross draft	Fixed high thermal mass	Down draft	Cross draft	Forced draft	Metal stove with heating wall
Liquid	Kerosene	Wick	Pre-ssure			Pressure	Lantern						
	Ethanol	Open dish	Pre-ssure			Pressure							
Gas	LPG/NG					Gas burner							
	Biogas					Gas burner							
	Dimethylether					Gas burner							

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