Energy for Sustainable Development 35 (2016) 1–6

Contents lists available at ScienceDirect

Energy for Sustainable Development

Probe-based measurements of moisture in dung fuel for emissions measurements

Sneha Gautam [a], Rufus Edwards [b,*], Ankit Yadav [a], Robert Weltman [b], Ajay Pillarsetti [c], Narendra K. Arora [a], Kirk R. Smith [c]

[a] Inclen Trust International, New Delhi, India
[b] Department of Epidemiology, University of California Irvine, CA, USA
[c] School of Public Health, University of California Berkeley, CA, USA

ARTICLE INFO

Article history:
Received 21 June 2016
Revised 25 August 2016
Accepted 1 September 2016
Available online xxxx

Keywords:
Cow dung
Water boiling test
Kitchen performance test
Brushwood
Energy content

ABSTRACT

Measurement of the moisture content of biomass fuels is critical for the measurement of emission factors and accounting for differences in stove performance results from standardized tests such as the water boiling test. Moisture probe measurements have been used systematically for the assessment of moisture content of woody fuels, as it is more convenient than laboratory-based oven-drying methods because multiple measurements can be rapidly performed on-site as the fuel for the cooking task is selected for use. Current protocols, however, state that the probes used to measure moisture content in wood cannot be used with dung, crop residues, or other non-wood fuels. The averages from 5 replicate moisture probe measurements on each of 35 cow and buffalo dung patties from Haryana, India, were compared to oven drying moisture measurement at 103 ± 2 °C. Dung patties were selected ranging in moisture content from 5% to 65% on a dry basis based on probe measurements with 5 unique patties in each 10% increment. The results showed good linearity between moisture probe ≤55% and oven drying methods ($r^2 = 0.76$). Results were then used to adjust uncontrolled measurements of dung moisture taken prior to cooking for 17 homes in 4 villages in rural Haryana, India, which demonstrate that the commonly used moisture probe, when calibrated against oven-based methods, can be used to assess moisture content of dung patties over the range of dung moisture typically found and used in villages for cooking purposes.

Introduction

Use of non-woody biomass for fuel, such as dung and crop residues, is prevalent in many areas of the world. While there have been considerable efforts to develop protocols and perform laboratory-based testing of stoves using wood fuels, there has been much less (1) testing of unprocessed, non-woody biomass and dung and (2) development of stoves suited to burning these fuels. Dung from a variety of animals (cows, water buffalo, yak, camel) is used in many parts of the world to cook food and heat homes, particularly in high-altitude areas above the treeline and in arid environments where biomass is scarce, but also in agricultural areas of India and Nepal. Emissions from and properties of dung fuels, however, are not well documented (Edwards et al., 2014), with only a handful of studies on emission factors from India (Venkataraman et al., 2002; GIRA, 2014; Venkataraman and Rao, 2001; Stone et al., 2010; Smith et al., 2000). Limited data indicate that emissions of particulate matter (PM), carbon monoxide (CO), and polycyclic aromatic hydrocarbons (PAH) from dung were considerably higher than those for fuel wood or woody briquettes (Venkataraman et al., 2002), and that advanced combustion stoves may not deliver the benefits anticipated when using these fuels (GIRA, 2014; Venkataraman and Rao, 2001).

Fig. 1 shows the global distribution of dung fuel use in stoves as the primary cooking fuel compiled using the U.S. AID Demographic and Health Surveys (DHS)[1] Program "STATcompiler" Version 1.5.2 and plotted in ArcGIS, ArcMap 10.2.2. Data for Afghanistan and Kyrgyzstan were provided by the most-recent Multiple Indicator Cluster Surveys (MICS) for each country.[2] The majority of dung use is in South Asia, with Afghanistan reporting the largest percentage of total energy use arising from dung combustion and India reporting the largest population using dung fuels for cooking. Dung use is also prevalent in Africa, but with much lower frequency, and at high altitudes in Peru. Although dung represents a small fraction of the total energy use in countries where dung use is prevalent, the number of people globally using dung for fuel is large and the emissions are high relative to other fuels. Based on population data for 2014 compiled in the World Development

* Corresponding author.
E-mail address: edwardsr@uci.edu (R. Edwards).

[1] http://www.dhsprogram.com/

[2] Data for Afghanistan came from the 2001–2011 MICS Final Report available at http://microdata.worldbank.org/ and data for Kyrgyzstan came from the 2014 Multiple Indicator Cluster Survey Final Report available at http://mics2014.kg/images/english.pdf.

http://dx.doi.org/10.1016/j.esd.2016.09.003
0973-0826/

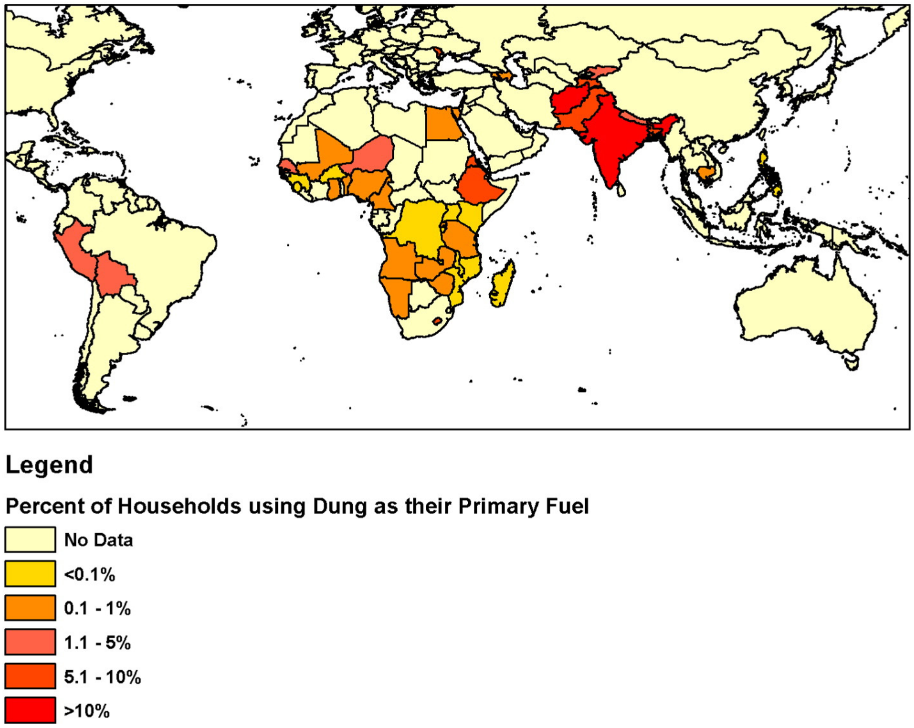
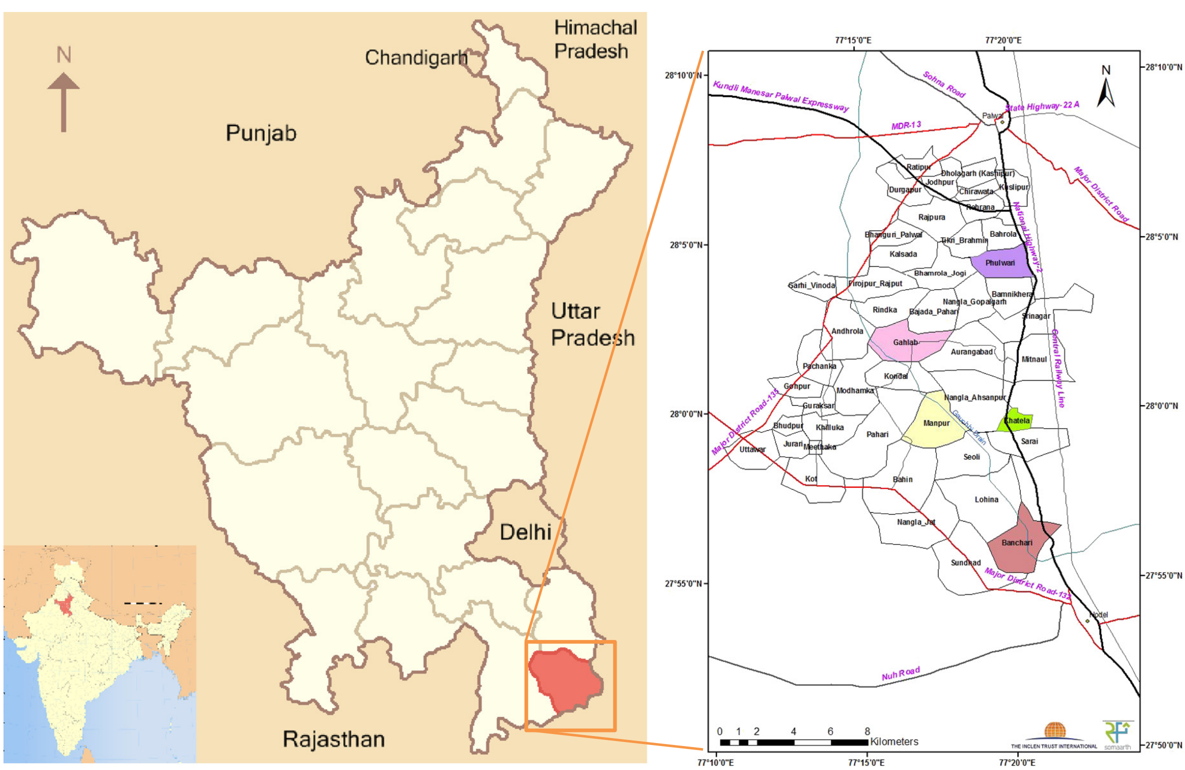


Fig. 1. Global distribution of dung fuel use in stoves for primary energy provision.



https://commons.wikimedia.org/wiki/File:HaryanaPalwal.png#file

Fig. 2. Palwal study site with villages where dung patties were collected.

Indicators database,[3] approximately 185 million individuals live in homes where cooking is primarily with dung.

[3] World Development Indicators database, World Bank, 11 April 2016 http://databank.worldbank.org/data/download/POP.pdf

Developing cleaner alternatives for dung fuels is therefore essential to reduce associated health burdens. A first step in this process is to improve the ease with which emissions from this fuel can be measured. Measurement of the moisture content of biomass fuels is critical for estimating emission factors and for accounting for differences between

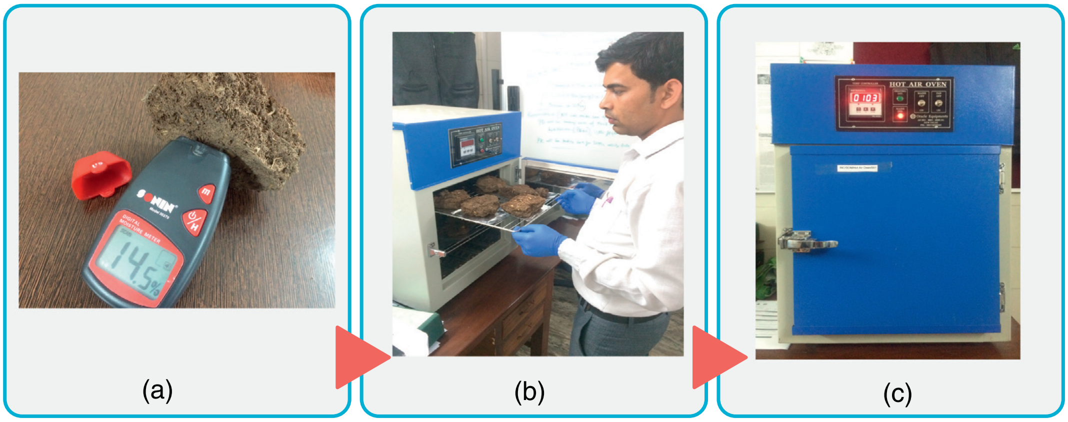


Fig. 3. Moisture measurements: (a) moisture meter with sample, (b) sample arrangement in convection oven and (c) convection oven.

stove performance results from standardized tests, such as the water boiling test. Moisture probe measurements have been used systematically for assessment of the moisture content of wood and brushwood fuels by measuring the conductivity between two sharp probes that are inserted into wood. Current protocols state that the moisture probe should not be used to measure the moisture content of dung, crop residues, or other non-wood fuels, greatly complicating the ease and logistics of measuring emissions. Here, we evaluate if simple moisture probes can be used, with the appropriate calibration, to assess the moisture content of dung patties in relation to oven drying, a standard method for estimating fuel moisture content, over the range of dung moistures typically found and used in villages in India where dung is a fuel for cooking.

Material and methods

Study area

The study was conducted within the SOMAARTH Demographic Development and Environment Surveillance Site (DDESS) in Palwal District, Haryana covering 51 villages (population approximately 200,000) (Fig. 2). The cow and buffalo dung patties for the comparison of moisture probe measurement techniques with oven drying methods were collected in Khatela village from August to September 2015. The uncontrolled field measurements, where dung was collected during cooking, were performed in Manpur, Gehlab, Banchari and Mitrol villages.

Comparison of moisture probe measurements with oven drying methods

The average of 5 individual moisture probe measurements from each of 35 dung patties were compared to moisture measured via oven drying at 103 ± 2 °C. All dung patties were obtained from real homes where dung was collected and manufactured into patties, and dried and stored for later use for cooking. Probe-based moisture measurements were conducted immediately in the field using a single digital moisture meter (model: 50270, SONIN Inc., China) by inserting the probes to their full length into the dung patty (Fig. 3a). Dung patties were selected to range in moisture content from 5% to 65%, with 5 patties in each 10-point increment, based on initial screening with the moisture probe of 5 measurements across the patty; on the edges, in the center and between the edge and center. After transportation to the field center., a sample of approximately 100 g was then broken off from each dung patty from the edge inward toward the center, and five individual moisture readings were recorded on the broken off portion; on the edges, in the center and between the edge and center. The sample was then wrapped in aluminum foil and kept in a plastic ziplock bag to minimize moisture and weight loss over time. Measurements for dung with moisture content of 55%–65% as assessed by the digital moisture meter were repeated to confirm results.

Measuring fuel moisture content by oven drying was performed by weighing each sample before placing on an aluminum tray in a temperature-controlled convection oven (Oracle Equipments, India) at 103 ± 2 °C until mass loss stopped on repeated weighing (24 h approximately) (Fig. 3b and c).

Analysis of elemental composition and energy content

Analysis of elemental composition and energy content were performed by Intertek India Private Limited utilizing ISO 1350 parts 1–4. Ash, along with nitrogen, sulfur carbon, and moisture %, were all calculated as a % of the total received weight of each fuel. Approximately 0.2–0.25 g of each sample was burnt in a flow of oxygen and the products were absorbed by suitable reagents and masses determined gravimetrically. Ash was weighed after thermal decomposition in the presence of excess oxygen. Oxides of nitrogen were retained by red lead, oxides of sulfur were retained by lead chromate, soda-asbestos was used in combination with anhydrous magnesium perchlorate to absorb water and carbon dioxide, and concentrated sulfuric acid contained in a bubbler was utilized to indicate the flow of oxygen and prevent any backflow to the absorbents.

Table 1
Variability in moisture contents across dung patties in each bin measured with the moisture probe and by oven drying.

Moisture content, wet basis (%)		05%–15%	15%–25%	25%–35%	35%–45%	45%–55%	55%–65%	55%–65%
Probe based	Mean	13.6	23.0	27.5	36.5	52.4	63.4	61.3
	SD	1.7	1.4	1.5	2.4	2.8	0.6	1.1
	COV	0.12	0.06	0.06	0.07	0.05	0.01	0.02
Oven drying	Mean	6.6	9.3	8.6	12.5	15.0	36.1	44.1
	SD	0.4	0.9	2.6	1.0	1.9	11.6	10.0
	COV	0.06	0.09	0.30	0.08	0.13	0.32	0.23

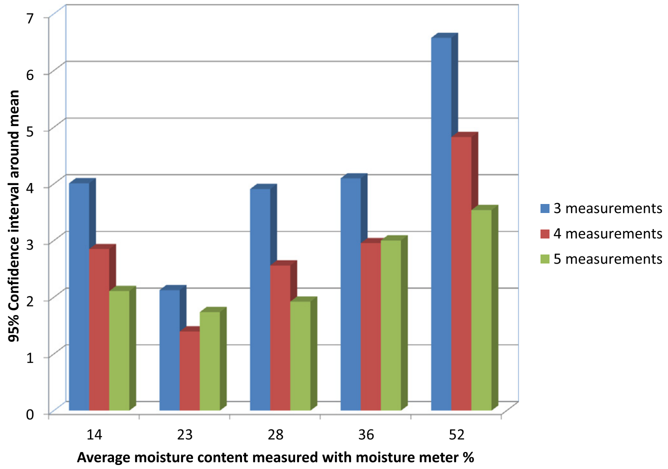


Fig. 4. Reduction in 95% confidence interval around mean with repeated probe measurements.

Results

Table 1 shows the mean, standard deviation and coefficient of variation (COV) for moisture content in each moisture-content bin measured with the moisture probe and by oven drying. Moisture meter measurements were made 5 times on each of the 5 samples in each bin, and oven drying measurements were made for each sample in each bin. In general, between dung patties in bins below 55% measured by the probe, the COV appears to be somewhat lower and more consistent due to the 5 repeated measurements of each dung patty compared to oven drying. Above 55%, the oven drying showed considerable variability in moisture content among the patties selected, which was not reflected in the probe measurements. The discrepancy between the probe and the oven drying was consistent when this bin was repeated to confirm results, indicating the probe measurements are not consistent above 55% measured by the probe.

Fig. 4 shows the reduction in 95% confidence intervals (95% CI) as successive probe measurements were made in individual patties in each bin. In general, the 95% CI increased at higher dung moisture content but were generally consistent at lower moisture contents, with the exception of the 15%–25% bin, where the probe measurements were very consistent. It is also apparent that a substantial reduction in the 95% CI was achieved when increasing the number of probe measurements in each patty from 3 to 5, although the difference between 4 and 5 is less apparent. As a result, 5 probe measurements of each patty achieved a good balance between ease of measurement and reduction in 95% CI around the mean.

Comparison between oven drying and moisture meter reading to assess moisture content

Fig. 5 shows the relationship between the average of 5 moisture probe measurements and the oven drying method to assess moisture content. It shows that moisture probe measurements increase linearly with oven-based moisture content on a wet basis between moisture probe measurements of 5% and 55%, but above 55%, the relationship with oven moisture content becomes unreliable. The relationship between moisture probe measurement below 55% and oven-based moisture content on a wet basis is shown in (Eq. (1)).

$$y = 0.21x + 3.86 \quad r^2 = 0.76; p < 0.001 \tag{1}$$

where y = oven-based moisture content (wet basis), and x = moisture probe measurement.

Fig. 6 shows a histogram of the average of 3 additional moisture probe measurements of 3 dung patties in 17 homes in 4 Haryana villages measured in 2014 and the corresponding histogram of estimated oven-based moisture content using Eq. (1). All moisture probe readings are less than or equal to the 55% cutoff point, with a median of 20%, demonstrating the moisture probe can be used to assess the moisture content in these homes using the relationship shown in Fig. 5. The two highest moisture probe measurements were 51% and 55%, which indicates that care must be taken to ensure values do not exceed the 55% cutoff; however, in controlled testing, women cooks from the region reported dung patties above 40% were hard to use for cooking tasks and drier patties were preferred.

Table 2 shows the ash, gross calorific value, sulfur, nitrogen and carbon content of brushwood (shrubs and twigs), fuelwood (stem wood), and dung used in Haryana, India. As expected, dung had a lower calorific value and greater ash content compared to the other fuels. In addition, dung was higher in sulfur relative to the other fuels, but had similar nitrogen content. Fuelwood and brushwood did not differ substantially, although moisture content was more variable in brushwood.

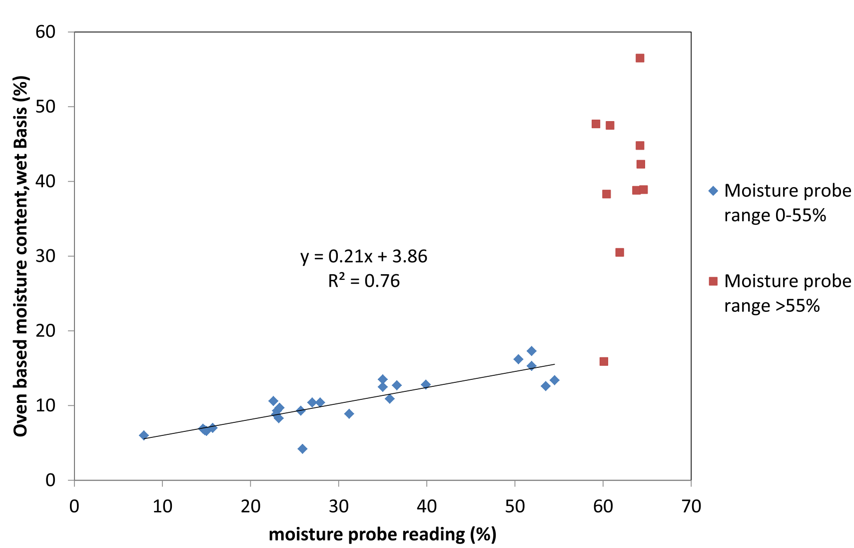


Fig. 5. Comparison between the average of 5 moisture probe measurements and oven drying methods to assess moisture content.

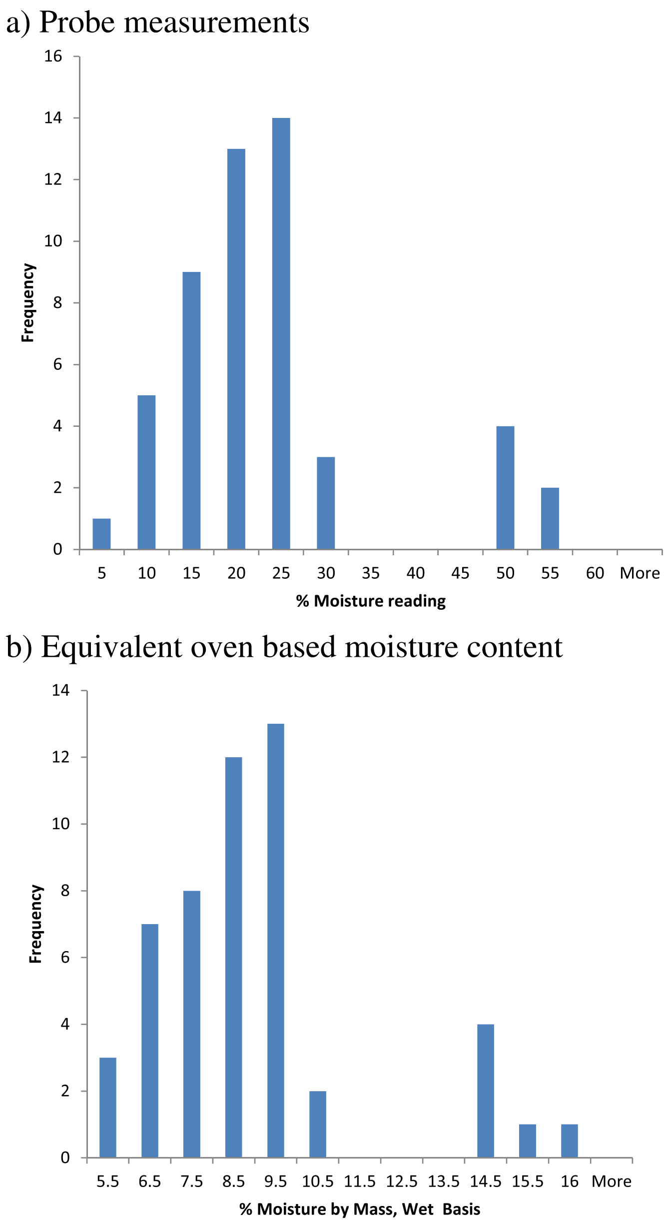


Fig. 6. Frequency histogram of 3 moisture probe measurements of dung fuel in 17 homes in 4 Haryana villages with conversion to oven-based moisture content;

Discussion

Measurement of the moisture content of biomass fuels is critical for the measurement of emission factors and accounting for differences in stove performance results from standardized tests such as the water boiling test.[4] The type, size and moisture content of fuel have a large effect on the outcome of stove performance tests. During the measurement of emission factors, moisture, carbon, and the energy content of fuel are used to estimate emissions in grams of carbon per kg dry fuel and/or per MJ. Moisture probe measurements are more convenient than oven-drying because multiple measurements can be rapidly performed on-site as the fuel is being selected for use. The measurements may also be adjusted for different species and calibrated for different ambient temperatures. Current protocols for the water boiling test 4.2.3 (Edwards et al., 2014), however, state that the moisture probe used to measure wood moisture content cannot measure the moisture content of dung, crop residues, or other non-wood fuels. As a result, the oven method to determine moisture content must be used, but this presents logistical difficulties in obtaining access to drying ovens and accurate balances in remote locations or to transporting fuels for later testing. The analysis presented here demonstrates that the commonly used moisture probe, when calibrated against oven-based methods, can be used to assess moisture content of dung patties over the range of dung moisture typically found and used in villages for cooking purposes. This is an advance in reducing the complexity and cost of making field measurements of emissions in real homes and also improves the ability of testers to rapidly assess moisture content during laboratory testing using the water boiling test or other protocols. Perhaps more importantly, the moisture meter can rapidly assess the moisture of each individual piece of fuel used in the water boiling test, or assess moisture in multiple patties that are used in cooking a meal. The scope and range of such measurements would not be feasible in field studies of many homes due to cost and logistical constraints of performing many oven drying tests. In situations where fuel moisture contents vary widely between individual pieces of fuel, such as in dung patties used in Indian villages, assessment of moisture in multiple patties used to cook a meal therefore allows more accurate assessment of the average moisture content of the whole fuel mixture used for cooking.

The calibration against oven drying here provides a best estimate when oven drying and weighing facilities are not feasible; however, this study is not intended to completely delineate the relationship between moisture probe measurements and oven drying. In particular, the study should be replicated in other geographies both in India and beyond to evaluate the generalizability of these relationships. This is particularly true if the dung patty manufacturing process differs substantially from the process in India or if animal diets are substantially different across evaluation sites. In addition, the relationship likely varies depending on the make and model of moisture probe, and testing should be performed on a broader range of devices to build up a database of coefficients.

Since many studies rely on literature-based values for carbon and energy content of wood and dung fuels to compute emissions factors as g carbon per MJ or per kg dry fuel, Table 2 shows these parameters for fuelwood, brushwood (shrub) and dung fuel in Haryana India. Overall, the carbon contents were relatively similar between fuels, with dung having the lowest percentage on an oven dry basis (17.4 ± 1.2), followed by brushwood (20.1 ± 2.0) and wood (20.8 ± 0.9). Not surprisingly, dung had the lowest energy content on an oven dry basis (13.8 ± 1.6 MJ/kg), followed by wood (17.8 ± 0.7 MJ/kg) and brushwood (20.4 ± 1.0 MJ/kg). Perhaps more surprising was the increased sulfur content of dung fuels, which when combined with the lower energy content will lead to greater emissions of sulfur-based compounds relative to brushwood and fuelwood. As with the moisture analysis, dung composition should be replicated seasonally to examine the impact of animal diets on composition, and also in other geographies both in India and beyond to evaluate the generalizability of these relationships.

Recommendations

The Water Boiling Test 4.2.3 is a normative reference indispensable for the application of IWA emission tiers of performance for cookstoves. Modification of the protocol to allow for the use of moisture probe meters to assess moisture content in dung patties would greatly simplify the requirement for laboratories and regional test centers in India and other dung-using areas.

Measurements with the moisture probe meter should be performed with the probes inserted fully into the dung patty, and 5 replicate measurements performed for each patty, on the edge, in the center, and between the edge and the center.

[4] http://cleancookstoves.org/technology-and-fuels/testing/protocols.html

Table 2
Ash, gross calorific value, sulfur, nitrogen and carbon content of brushwood, fuelwood, and dung used in Haryana, India.

Sample	n	Moisture	Ash	Gross calorific value	Sulphur	Carbon	Nitrogen
		% WT*	% WT**	MJ/kg**	% WT**	% WT**	% WT**
Brushwood	5	12.7 (±8.0)	4.3 (±2.0)	20.4 (±1.0)	0.13 (±0.06)	20.1 (±2.0)	1.4 (±0.3)
Fuelwood	3	8.2 (±0.5)	3.9 (±0.8)	17.8 (±0.7)	0.11 (±0.03)	20.8 (±0.9)	1.2 (±0.4)
Dung	5	10.1 (±0.8)	32.8 (±5.5)	13.8 (±1.6)	0.28 (±0.02)	17.4 (±1.2)	1.4 (±0.1)

* : Reported on a received basis.
** : Reported as the fraction of oven-dry weight.

In addition to dung, there are other non-woody fuels, including a large variety of crop residues, that should be assessed and calibration factors established against oven drying moisture methods to allow widespread application of moisture meters to simplify emissions measurements.

Acknowledgements

This research was supported by EPA STAR R83503601 Characterization of Emissions from Small, Variable Solid Fuel Combustion Sources for Determining Global Emissions and Climate Impact; and R835425 Impacts of household sources on outdoor pollution at village and regional scales in India. The contents are solely the responsibility of the authors and do not necessarily represent the official views of the U.S. EPA. The U.S. EPA does not endorse the purchase of any commercial products or services mentioned in the publication.

References

Edwards R, Karnani S, Fisher EM, Johnson M, Naeher L, Smith KR, et al. Review 2: Emissions of Health-Damaging Pollutants from Household Stoves. WHO Indoor Air Quality Guidelines: Household fuel Combustion; 2014.
GIRA. Use, displacement and field performance of advanced-combustion stoves—evaluation guidelines for fuel-device stacking contexts. Final project report. UN Foundation; 2014.
Smith KR, Uma R, Kishore VVN, Zhang JF, Joshi V, Khalil MAK. Greenhouse implications of household stoves: an analysis for India. Annu Rev Energy Environ 2000;25:741–63.
Stone EA, Schauer JJ, Pradhan BB, Dangol PM, Habib G, Venkataraman C, et al. Characterization of emissions from South Asian biofuels and application to source apportionment of carbonaceous aerosol in the Himalayas. J Geophys Res Atmos 2010;*115*(D6). [n/a-n/a].
Venkataraman C, Rao GUM. Emission factors of carbon monoxide and size-resolved aerosols from biofuel combustion. Environ Sci Technol 2001;35(10):2100–7.
Venkataraman C, Negi G, Brata Sardar S, Rastogi R. Size distributions of polycyclic aromatic hydrocarbons in aerosol emissions from biofuel combustion. J Aerosol Sci 2002; 33(3):503–18.