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Comparative performance of five Mexican plancha-type cookstoves using water boiling tests



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ABSTRACT

While plancha-type cookstoves are very popular and widely disseminated in Latin America, few peer review articles exist documenting their detailed technical performance. In this paper we use the standard Water Boiling Tests (WBT) to assess the energy and emission performance of five plancha-type cookstoves disseminated in about 450 thousand Mexican rural homes compared to the traditional 3-stone fire (TSF). In the high-power phase, average modified combustion efficiencies (MCE) for plancha-type stoves were $97 \pm 1\%$ which was higher than TSF $93 \pm 4\%$, and reductions in CO and PM_{2.5} total emissions were on average 44%. Time to boil and specific fuel consumption, however, were increased in plancha-type stoves compared to the open fire as a result of the reduced overall thermal efficiency of the plancha during WBT. In the simmering phase, plancha-type stoves showed much more consistent performance reductions compared to the TSF. MCE for plancha stoves were on average $98 \pm 1\%$ and $95 \pm 3\%$ for the TSF, while reductions in CO and PM_{2.5} total emissions were on average 55%. In this phase 27% average savings in fuel use are achieved by plancha-type stoves. Removal of the plancha rings resulted in savings of specific fuel consumption (SFC), thermal efficiency (TE), and time to boil; however, CO and PM_{2.5} emissions increased significantly as flue air is drawn through the comal surface rather than through the combustion zone, resulting in suboptimal combustion conditions.

International Workshop Agreement (IWA) energy performance Tiers for plancha-type stoves ranged from 0 to 1. However, these results contrast sharply with the well documented reductions in fuel consumption during daily cooking activities achieved by these stoves. IWA indoor emissions Tiers are 4 for both PM_{2.5} and CO using locally measured values for fugitive emissions. Optimization of combustion chamber design on these stoves in Mexico is desirable to further reduce indoor emissions and to reduce the impacts of neighborhood pollution that can re-infiltrate kitchens. Comparison of performance between plancha-type stoves and unvented stoves should reflect the substantial gains that are made by reducing indoor air pollution and exposures by venting pollutants.

1. Introduction

Plancha-type cookstoves have been widely disseminated in Mexico as they are well suited to local cooking customs and are widely accepted in local communities [1]. Between 2007 and 2012 a total of more than 600,000 plancha-type stoves had been disseminated, mostly through the *Programa Nacional de Estufas de Leña* [2]. Recently, assessment

of cookstoves technical performance has been integrated into a standardized guidance through an International Workshop Agreement (IWA) 11:2012 of the International Standards Organization [3], that provide performance Tiers of efficiency, emissions and safety [4]. Although there is a standard for total emissions, ISO standards to protect health largely address open combustion type stoves, and stoves without flues. There is a clear exposure benefit that

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well-functioning chimney stoves provide as only a fraction of the emissions enter the kitchen via fugitive emissions and re-infiltration. The World Health Organization (WHO) Indoor Air Quality Guidelines present emission rates for both vented and unvented stoves, where the emission rate for vented stoves used a normal distribution for the fraction of emissions entering the kitchen, ranging from 1 to 50% with a mean of 25% and standard deviation of 10% of the emissions from an unvented stove [5]. The IWA standards were established with Tiers for indoor emissions, which represent fugitive emissions for a stove with a flue, and total emissions based on reductions in emissions rates in a transition from open fires to modern forced draft stoves. Cognizant of the gaps in information for specific stove, IWA workshops recommended that new protocols be developed or current protocols be updated to more adequately address a larger number of stove and fuel types, such as heating stoves, plancha stoves, charcoal stoves, double pot stoves and solar cookers [6].

In this paper we examine the energy and emission performance of 5 Mexican plancha-type stoves in comparison with a 3-stone fire (TSF) using standard Water Boiling Tests (WBT). We highlight the issues involved in incorporating plancha-type stoves into IWA guidance. We examine the reasons for poor performance of plancha-type stoves in WBT in relation to actual performance during daily cooking tasks in real homes, and suggest some modifications to test protocols to better reflect the actual performance of these stoves. These suggestions can be useful for IWA current activities on adapting the WBT for plancha stoves.

2. Methods

2.1. Stoves distribution

Fig. 1 shows the 5 plancha-type stoves tested: Patsari, Patsari Portatil, ONIL, Mera-Mera, and Ecostufa. Distribution of the Patsari has been approximately 200,000 in several Mexican States such as Michoacan, Oaxaca, Sinaloa, and others. Distribution of the ONIL has been approximately 90,000 predominantly in Guerrero, Oaxaca, San Luis Potosí, and Chiapas. The extent of Mera-Mera and Ecostufa distribution is not known precisely, but several thousands have also been distributed in different Mexican States. The total estimated distribution is more than 450 thousand stoves installed in the field. The Patsari stove is built in-situ and the rest are mass-produced. The ONIL and Mera-Mera have metallic rings insert in the plancha surface that can be removed to improve the heat transfer pot to comal⁵ (see [Supplementary section](#) for more detailed information about each stove tested). The ONIL and ONIL without rings were evaluated to highlight the impact of the plancha surface in changing emission and performance metrics as can be seen in Fig. 2.

2.2. Water boiling test

The WBT protocol version 4.1.2 [7] was used to determine performance and emission parameters of the plancha-type stoves and the TSF. All plancha-type stoves were started with a small amount (~30 g) of “ocote” that is a highly resinous piece of pitch pine. For all three phases of the WBT protocol, a digital scale with 1 g resolution was used to determinate measurements of the mass of fuel used. White oak (*Quercus bicolor*) was used in all WBT test, and the average dimensions of fuel were 2 cm×4 cm×40 cm. Fuel moisture was determined by a Protimeter Timbermaster Wood Moisture Meter, and nine measurements for each test for each stove were made [8]. The average fuelwood moisture content for all tests was $8.8 \pm 1.4\%$ on a wet basis with a range of 7–13%.

⁵ Comal is a flat metal surface lying immediately over the combustion zone on which food items and pots to cook food are placed.



Fig. 1. Stoves tested. Left to right: Ecostufa, Mera-Mera, Patsari Portatil, 3-stone fire, ONIL and Patsari.

2.3. Emission measurements

Emission measurements were made using a Portable Emissions Measurement System (PEMS) (Aprovecho Research Center, Oregon USA), consisting of a hood under constant flow which collects emissions from the cookstove being tested. Real-time concentrations are measured using a NDIR (non-dispersive infrared) sensor for CO₂, an electrochemical cell to measure CO, and a light scattering photometer to estimate PM_{2.5}. CO₂ and CO sensors were calibrated using zero air and a mixture of 100 ppm CO and 3000 ppm CO₂ [9]. Constant flow hoods have been used previously to capture and measure emissions from cookstoves in laboratory or simulated kitchen settings [10–13].

Light scattering by particles is dependent on the scattering coefficient of particles, mass scattering cross section and the particle size distribution [14], PEM PM_{2.5} light scattering measurements were referenced to simultaneously collected gravimetric filter based measurements from in-lab testing using the same stove and wood type by the following adjustment factors:

$$\text{Patsari: } (y[\text{PM}_{2.5,\text{filter}}]=5.1[\text{PM}_{2.5,\text{optical}}]+5417), R^2=0.84, \quad (1)$$

$$\text{Ecostufa: } (y[\text{PM}_{2.5,\text{filter}}]=19[\text{PM}_{2.5,\text{optical}}]+2690), R^2=0.90, \quad (2)$$

$$\text{ONIL: } (y[\text{PM}_{2.5,\text{filter}}]=11[\text{PM}_{2.5,\text{optical}}]+2667), R^2=0.99, \quad (3)$$

where $[\text{PM}_{2.5,\text{filter}}]$ and $[\text{PM}_{2.5,\text{optical}}]$ are filter and optical PM_{2.5} concentration, respectively. Eq. (1) was used to adjust Patsari Portatil and Mera-Mera PM_{2.5} light scattering concentrations as filter data were not available for these measurements.

2.4. Data analysis

When the number of replicates is small, the t-test is recommended over ranked transformations and the Welch test [15]. Statistical analysis of difference in means was done using a two sample t-test, and probability of error of $p \leq 0.05$ was considered statistically significant as reported by Grimsby et al. [16] and Berrueta et al. [17], respectively. Coefficient of variation (CV) and t-distribution for plancha-type stoves performance during WBT phases are shown in [Appendix A, Table A1](#). The 95% confidence interval (CI) indicates the reliability of the means based on the number of test replicates, where the true mean has 95% chance of lying within the confidence interval. Emissions reductions and 95% CI from plancha-type stoves relative to TSF are shown in [Table A2](#).

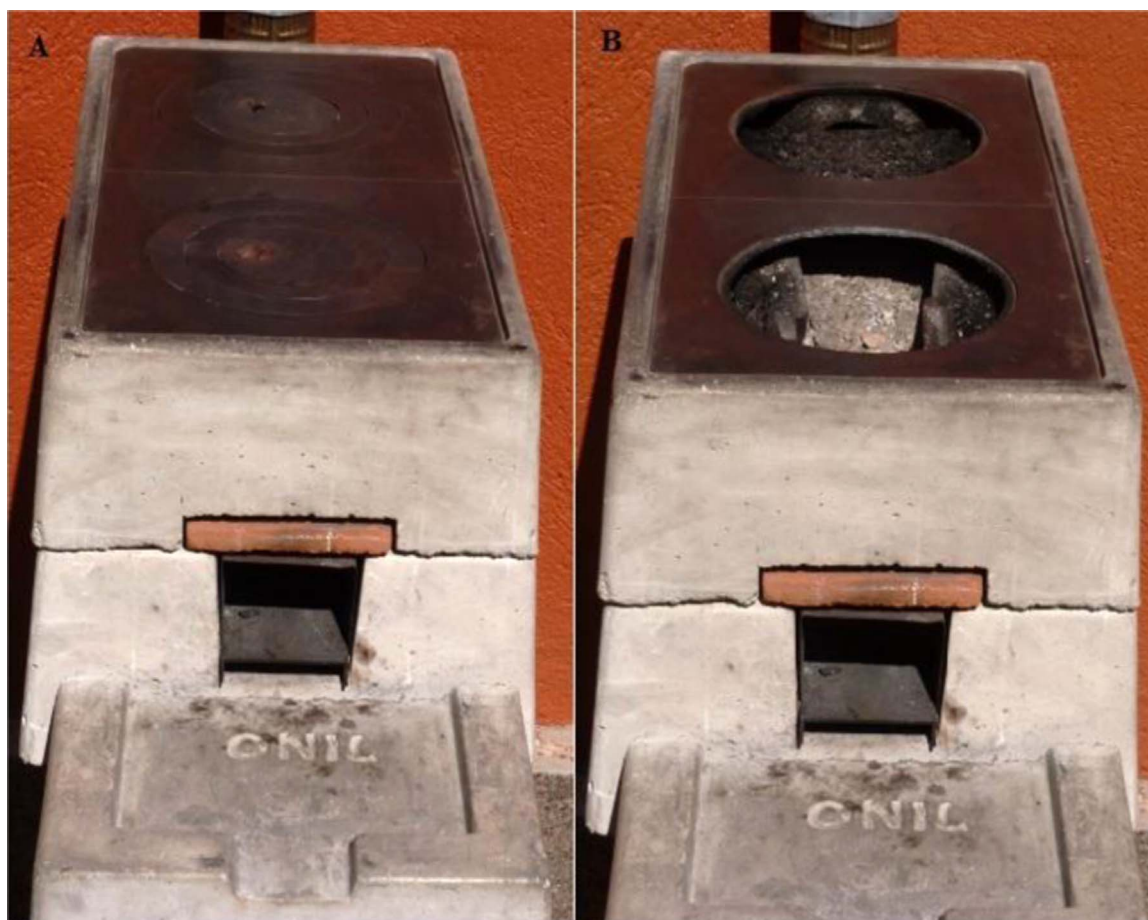


Fig. 2. ONIL stove: (A) Plancha surface. (B) Rings in plancha surface removed.

3. Results

3.1. Performance parameters

Unadjusted PEMS light scattering PM_{2.5} concentrations underestimated particle concentrations by a factor of 10 and 15 relative to gravimetric filter based measurements depending on the specific stove, demonstrating the importance of referencing light scattering measurements to gravimetric concentrations. In fact, IWA protocols recommend that both gravimetric and light scattering methods to be used, and some studies [18,19] have demonstrated the need to reference light scattering measurements to gravimetric concentrations to ensure that the measurements are comparable between the two methods and

across different testing centers.

Table 1 shows average specific fuel consumption (SFC), thermal efficiency (TE), firepower, and time to boil for high and low power phases of five repeat WBT tests of 5 plancha-type stoves compared to TSF. In the high power phase, TSF showed the lowest time to boil with 20 ± 5 min which is similar as reported by [10,20], and its SFC was 0.1 ± 0.1 kg/L in relatively good agreement with prior studies [17]. TE for Patsari stove was 12 ± 1%, but TSF demonstrated statistically higher thermal efficiency which also was observed by Bailis et al. [20]. During simmering phase, SFC for TSF was 0.2 ± 0.1 kg/L which is significantly different from the 0.1 ± 0.1 kg/L obtained for all plancha-type stoves. The highest CVs obtained when estimating SFC, TE, and firepower was 26% as can be seen in Table A2. In the time to boil, however, the ONIL

Table 1

Average performance parameters of plancha-type stoves and TSF for both WBT phases.

Phase	Parameter	TSF	Patsari	Patsari Portatil	Mera-Mera	Ecostufa	ONIL
High power: cold and hot start	SFC (kg/L)	0.1 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
	TE (%)	15 ± 1	12 ± 1	8 ± 1	16 ± 3	19 ± 3	15 ± 2
	Firepower (kW)	11 ± 3	10 ± 2	11 ± 2	9 ± 1	9 ± 2	8 ± 2
	Time to boil	20 ± 5	43 ± 15	38 ± 11	48 ± 13	36 ± 12	62 ± 28
Low power	SFC (kg/L)	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
	TE (%)	15 ± 1	13 ± 1	11 ± 1	22 ± 1	20 ± 1	17 ± 2
	Firepower (kW)	4 ± 1	7 ± 1	7 ± 1	6 ± 1	6 ± 1	5 ± 1

Note: A total of 5 tests were conducted for each stove and TSF, and average of high and low power phases is shown. Variability is expressed as ± standard deviation.

Table 2
Average emission contribution for Plancha-type stoves and TSF during the high and simmer phases.

Phase	Parameter	TSF	Patsari	Patsari Portatil	Mera-Mera	Ecostufa	ONIL
High power: cold and hot start	MCE (%)	93 ± 4	97 ± 1	97 ± 1	96 ± 1	98 ± 1	99 ± 1
	g(c)CO/kg(c)CO ₂	81 ± 43	31 ± 13	35 ± 13	40 ± 13	19 ± 6	13 ± 7
	gCO ^a	59 ± 31	43 ± 12	41 ± 9	44 ± 11	22 ± 8	20 ± 9
	gPM _{2.5} ^a	5.3 ± 2.9	2.5 ± 0.9	3.0 ± 0.8	3.5 ± 1.2	2.9 ± 1.0	3.0 ± 1.1
Low power	MCE (%)	95 ± 3	98 ± 1	99 ± 1	98 ± 1	99 ± 1	98 ± 1
	g(c)CO/kg(c)CO ₂	52 ± 28	15 ± 5	15 ± 5	18 ± 7	11 ± 2	17 ± 10
	gCO ^a	33 ± 12	17 ± 8	18 ± 7	17 ± 8	11 ± 3	14 ± 8
	gPM _{2.5} ^a	4.4 ± 1.1	1.8 ± 0.3	1.9 ± 0.6	2.2 ± 0.4	2.2 ± 0.6	1.6 ± 0.5

Note: Variability is expressed as ± standard deviation.
^a Total emissions as reported by Yuntewi et al. [30]. Average of high and low power phases is shown.

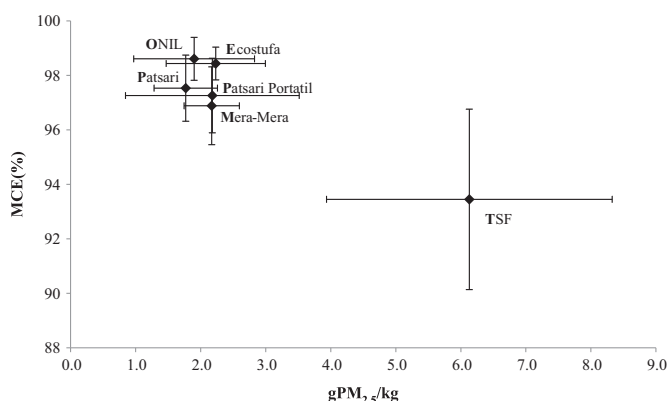


Fig. 3. Average of PM_{2.5} emission factors and MCEs for plancha-type stoves and TSF. Note: Error bars represent ± standard deviation.

stove presented a CV of 46% due to its larger variation to reach boiling point in both cold and hot phases.

Table 2 shows average emissions contribution plancha-type stoves and TSF for high power and low power phases of five repeat WBT tests. Overall, plancha-type stoves all showed large emission reductions relative to the TSF. Reductions in CO total emissions in the high-power phase ranged between 26% and 67%, depending on the stove. Reductions in PM_{2.5} total emissions ranged between 35% and 52% with the ONIL and the Patsari stove showing the largest values, depending on the pollutant. Average reductions for plancha-type stoves in the simmering phase relative to the TSF were substantial and statistically significant with 54% for CO and 56% for the PM_{2.5}, with the Ecostufa and ONIL showing the largest reductions, respectively. In addition, reductions in CO emission ratios in the high and low power phases were on average 66% and 71%, respectively, and differences were statically significant at 95% confidence.

Fig. 3 shows average of modified combustion efficiencies (MCE) and PM_{2.5} emission factors for plancha-type stoves and TSF. MCEs for ONIL (99 ± 1%), Ecostufa (98 ± 1%), Mera-Mera (97 ± 1%), Patsari (98 ± 1%), and Patsari Portatil (97 ± 1%) were higher than the TSF (93 ± 3%). MCEs for the TSF and ONIL stove were comparable between this study and those reported by Jetter et al. [21], and MCE for Patsari stove is also in a good agreement with reported combustion efficiencies [8]. Average PM_{2.5} emission factor (gPM_{2.5}/kg dry wood) for the five plancha-type stoves was 2.0 ± 0.2 gPM_{2.5}/kg which is 3 times lower than the TSF (6.1 ± 2.2 gPM_{2.5}/kg) and differences between the stoves

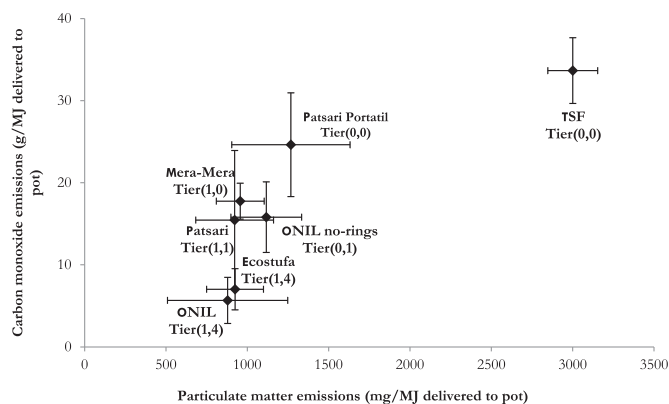


Fig. 4. High-power CO and PM_{2.5} emissions for Plancha-type stoves and TSF using IWA metrics. Note: Error bars represent ± standard deviation.

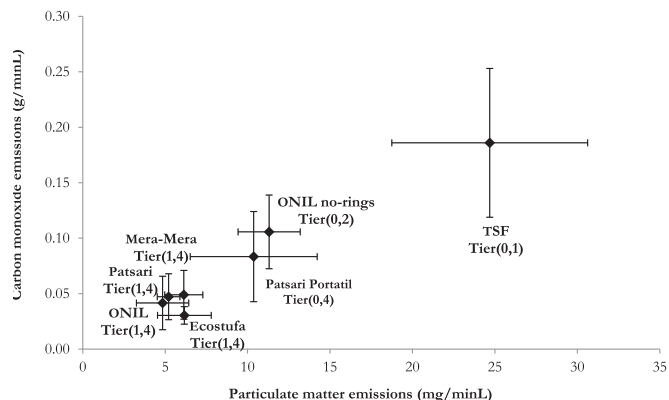


Fig. 5. Low-power CO and PM_{2.5} emissions for Plancha-type stoves and TSF using IWA metrics. Note: Error bars represent ± standard deviation.

tested and the TSF were statistically significant at 95% confidence level.

3.2. IWA performance metrics

Figs. 4 and 5 and Table A3 compare the different stoves tested in terms of the IWA efficiency and emission performance metrics. *Efficiency*: the highest thermal efficiency Tier achieved by plancha-type stoves was by the ONIL without rings with Tier 1 (21 ± 1%), the

rest of Plancha-type stoves with metallic surfaces separating the combustion zone from the pot were Tier 0. *Emissions*: for CO emissions, during high-power phase, Tiers ranged from 0 for Patsari Portatil and Mera-Mera, to 4 for Ecostufa and ONIL. For the low-power phase, most stoves achieved Tier 4 for CO emissions. Regarding $PM_{2.5}$ emissions, most stoves achieved Tier 1 in both high- and low-power phases. *Indoor emissions*: we measured fugitive emissions in a set of 18 WBT conducted in the five plancha-stoves examined, for a total of 54 measurements. The results indicate that fugitive emissions average 1% (with a 95% CI $\pm 0.3\%$). Using this value, to estimate CO and $PM_{2.5}$ indoor emissions for Plancha-type stoves we obtain a Tier 4 for both pollutants.

4. Discussion

Plancha-type stoves have substantially higher modified combustion efficiencies and reduced overall emissions (Fig. 3), however, thermal efficiencies in WBT are comparable or lower than the TSF because the plancha-type stoves have a metal plate that separates the pot from the combustion zone, which allows for a flue that vents emissions outdoors. While indoor emissions are substantially less than open fire stoves that vent directly into indoor environments, optimization of combustion chamber design on these plancha-type stoves in Mexico is desirable to further reduce indoor emissions and to reduce the impacts of neighborhood pollution that can re-infiltrate. Thus there is still considerable room for improvement in these stove designs.

In WBTs all plancha-types stoves showed low overall TEs, comparable or lower than the TSF (see Table 1), confirming previous studies (see for example [21]). This would imply little or no fuel savings of the stove compared to the traditional TSF. However, in field tests of fuel consumption, most of these stoves lead to fuel savings of more than 50% with regards to the TSF [17,22]. The reason for these somewhat contradictory findings threefold.

First, real cooking involves many factors that are not captured in laboratory tests [23,24], which is why WBTs are not representative of the situation in rural villages, or of climate benefits through carbon offsets [24–26]. Second, Plancha stoves show a poor energy and emissions performance when they are forced to boil a large volume of water, but boiling this amount of water is not representative of cooking of local staples in rural communities of Mexico and Central America. During simmering tests Plancha stoves consistently show much better MCE compared to high power tests because the combustion chamber tends to be overloaded restricting airflow when trying to boil large volumes of water, but during simmering air flow into the combustion chamber is sufficient to combust the available gases. Only one stove, the ONIL, showed similar efficiencies in both phases. Thirdly, the WBT underestimates the actual TE of these stoves because only a small portion of the comal heat transfer is used for boiling water [18], whereas the whole surface is used for cooking staple foods such as tortillas.

Current efforts to address these shortcomings of the WBT include, (a) testing in 2 modes: (1) with typical cooking pots and (2) with water in contact with 60% of the surface area of the plancha using a shallow pot (named “comalolla”) covering the whole comal surface to better represent the actual plancha heat transfer efficiency, or the “Mylar pot” method [27]. However, the evaporative losses of such a system would have to be accounted for when comparing with standard pots used of water boiling tests, or foam covers used on the water surface to minimize evaporative losses [28]; and (b) weighting the results of the different phases of the water boiling test by the relative proportions of boiling and simmering seen in the field through the use of a burn cycle [24], or comparing across performance curves [29]. Alternatively the effectiveness of the stoves could be evaluated with other tasks such as tortilla making in controlled cooking tests. However, this limits the

utility of the data in comparing stoves between different regions in a standard manner, as food staples differ across global regions.

The results presented here are the most comprehensive database collected to date using similar protocols, operators, and equipment for each test, representing a large share of plancha-type stoves in Mexico. The results represent a baseline of performance of plancha-type stoves with the WBT, and confirm that alternative approaches to testing these stoves are required in this region. The results also show that improvements in the design of these stoves are still needed. As a basis for improving test protocols these results show that simply removing comal rings to perform a WBT will not likely produce results that are meaningful, as it changes the combustion of the stove. Analysis of the specific impact of the *plancha* surface or *comal* on heat transfer and emissions is not straightforward as removal of the rings in the plancha surface changes the combustion conditions inside the stove. When rings are removed emissions are vented directly into the room, and air passing through the stove as a result of draw of the flue can by-pass going through the combustion zone, passing through the stove surface instead and up the chimney. Thus, airflow through the combustion zone is reduced which decreases the combustion efficiency. A comparison of the performance and emission parameters of the ONIL stove with a plancha and with the rings in the plancha surface removed is shown in Table 3. ONIL without rings demonstrated average reductions of 20% and 30% in SFC and time to boil, respectively, and there is 20% increase in TE as the heat transfer from the pot to the comal was improved. In contrast however, average CO and $PM_{2.5}$ total emissions and CO gaseous emission ratio from the ONIL without rings were 2.6, 1.3, and 3.2 times higher than ONIL, respectively, and differences between the stoves were statistically significant with a 95% confidence level. Thus, removal of the rings results in a tradeoff between increased heat transfer, and reduced MCE resulting in increased emissions.

Plancha-type stoves generally perform poorly on IWA Tiers compared to unvented stoves, with the exception of indoor emissions and stove safety Tiers. While this would lead many to dismiss these stoves, they are widely accepted and used in Mexico and other parts of Central America, and, as shown by our data, there is a clear exposure benefit that well-functioning chimney stoves provide. IWA has already recognized the problem, and has called for developing modified WBT adequate to plancha-type stoves.

Since the objectives of most stove programs are to reduce adverse health impacts, the performance characteristics of vented and unvented stoves need to be treated separately, with due consideration given to the substantial gains that are made by reducing indoor air pollution and exposures by venting pollutants outside. Finally performance testing should better reflect the actual cooking uses for which the stove is typically being used, which will substantially impact performance characteristics of plancha-type stoves.

5. Conclusions

This study makes a comparative evaluation of the 5 major Plancha-type stoves disseminated in Mexico. Results show that:

- Plancha-type stoves show substantial reductions in CO and $PM_{2.5}$ emissions compared to the 3-stone fire with WBT, but optimization of combustion chamber design on these plancha-type stoves in Mexico is desirable to further reduce the impacts of neighborhood pollution that can re-infiltrate.
- In the low-power phase of the water boiling test, Plancha stoves reported substantial improvements in emission and fuel savings with respect to high-power phases, indicating the combustion chamber tends to be overloaded restricting air supply during high power tasks.
- As expected removal of the plancha rings resulted in reductions of

Table 3

Average performance and emissions parameters of ONIL stove with plancha surface and with rings in plancha surface removed.

Phase	Stove	SFC (kg/L)	TE (%)	Firepower (kW)	Time to boil (min)	MCE (%)	g (c)CO/kg (c)CO ₂	gCO ^a	gPM _{2.5} ^a
High power: cold and hot start	ONIL	0.2 ± 0.1	15 ± 2	8 ± 2	62 ± 28	99 ± 1	13 ± 7	20 ± 9	3.0 ± 1.1
	ONIL no rings	0.1 ± 0.1	21 ± 3	7 ± 2	44 ± 14	95 ± 2	49 ± 18	55 ± 16	3.9 ± 1.0
Low power	ONIL	0.1 ± 0.1	17 ± 2	5 ± 1	–	98 ± 1	17 ± 10	14 ± 8	1.6 ± 0.5
	ONIL no rings	0.1 ± 0.1	19 ± 4	4 ± 1	–	96 ± 1	38 ± 11	29 ± 9	2.8 ± 1.8

Note: Variability is expressed as ± standard deviation.

^a Total emissions. Average of high and low power phases is shown.

SFC and time to boil, however, CO and PM_{2.5} emissions increased significantly as flue air is drawn through the comal surface rather than through the combustion zone, resulting in suboptimal combustion conditions.

5.1. Recommendations for protocol modifications

- Performance tests to better represent the actual energy performance of plancha-type stoves should focus on better representing the heat transfer through the surface with *comalolla* or mylar pot methods, and not through performing a WBT with the rings removed.
- There is a need to better integrate the different phases of laboratory performance tests by weighting to reflect the actual performance in the field through representative regional stove burn cycles [24].
- Although the WBT 4.2.3 states that fugitive emissions should be measured separately there is no protocol for doing so as part of emissions testing for plancha stoves. Protocols for assessment of fugitive emissions need to be developed and implemented.

Appendix A

See Appendix Tables A1–A3.

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Table A1
Coefficient of variation and t-distribution for plancha-type stoves.

Parameter	Phase	p-Value										CV (%)									
		Patsari	Patsari	Patsari	Mera-Mera	Mera-Mera	Ecostufa	ONIL	ONIL-no rings	ONIL-no rings	ONIL-no rings	Patsari	Patsari	Patsari	Mera-Mera	Mera-Mera	Ecostufa	ONIL	ONIL-no rings	ONIL-no rings	
gCO	High power	0.2	0.1	< 0.05	0.7	< 0.05	< 0.05	< 0.05	0.5	< 0.05	< 0.05	28	22	25	25	35	45	28	28	28	
	Low power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.7	< 0.05	< 0.05	48	40	44	44	24	58	29	29	29	
gPM _{2.5}	High power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.1	< 0.05	< 0.05	37	27	35	34	37	37	26	26	26	
	Low power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.2	< 0.05	< 0.05	14	30	17	28	33	33	64	64	64	
g(c)CO/kg(c)CO ₂	High power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	42	38	32	33	33	56	37	37	37	37	
	Low power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.3	< 0.05	< 0.05	31	34	39	21	60	29	29	29	29	
MCE (%)	High power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	1	1	1	1	1	1	1	2	2	2	
	Low power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.3	< 0.05	< 0.05	1	1	1	1	1	1	1	1	1	
SFC (kg/L)	High power	< 0.05	< 0.05	< 0.05	0.2	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	16	14	34	15	15	27	17	17	17	17	
	Low power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	6	8	8	5	5	3	26	26	26	26	
TE (%)	High power	< 0.05	< 0.05	< 0.05	0.5	< 0.05	< 0.05	0.6	< 0.05	< 0.05	10	12	19	14	14	12	15	15	15	15	
	Low power	< 0.05	< 0.05	< 0.05	0.1	< 0.05	< 0.05	0.9	0.5	< 0.05	6	5	3	8	8	11	20	20	20	20	
Firepower (kW)	High power	0.8	0.9	< 0.05	0.1	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	21	21	13	24	24	22	22	22	22	22	
	Low power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.3	< 0.05	12	6	7	5	5	1	14	14	14	14	
Time to boil (min)	High power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	36	28	28	28	34	46	32	32	32	32	
	Low power	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	36	28	28	28	34	46	32	32	32	32	

Note: Plancha-type stoves were tested against TSF using a t-distribution with $\alpha=0.05$.

Table A2
Average percentage reductions and 95% confidence intervals (CI) for plancha-type stoves relative to the 3-stone fire (TSF).

Parameter	Phase	Patsari		Patsari Portatil		Mera-Mera		Ecostufa		ONIL	
		%	CI	%	CI	%	CI	%	CI	%	CI
gCO	High power	28	17 ± 22	30	18 ± 21	26	15 ± 22	63	37 ± 21	67	40 ± 27
	Low power	50	17 ± 15	47	16 ± 14	47	16 ± 15	67	22 ± 13	58	19 ± 15
gPM _{2.5}	High power	52	2.8 ± 2.0	44	2.3 ± 2.0	35	1.8 ± 2.1	45	2.4 ± 2.1	42	2.3 ± 2.1
	Low power	59	2.6 ± 1.2	57	2.5 ± 1.3	51	2.2 ± 1.2	49	2.1 ± 1.3	63	2.8 ± 1.3
g(c)CO/kg(c)CO ₂	High power	62	51 ± 30	57	46 ± 30	51	41 ± 30	77	63 ± 29	84	68 ± 29
	Low power	71	37 ± 29	71	37 ± 29	66	35 ± 29	79	41 ± 29	67	35 ± 31

Note: The column “%” means percentage reduction with respect to TSF. Percentage reductions were estimated as [(emission (TSF)–emission (plancha-type stove))/emission (TSF)]*100% as reported by Adkins et al. [31] and 95% CIs were estimated using: $\bar{X}_1 - \bar{X}_2 \pm t_{1-\alpha/2} S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$, where $S_p^2 = \frac{S_1^2(n_1 - 1) + S_2^2(n_2 - 1)}{n_1 + n_2 - 2}$, $t_{1-\alpha/2}$ is obtained from tables, and \bar{X}_1 was considered as the TSF.

Table A3
IWA performance metrics of plancha-type stoves and TSF.

IWA performance metrics	Units	TSF	Tier	Patsari	Tier	Patsari Portatil	Tier	Mera-Mera	Tier	Ecostufa	Tier	ONIL	Tier	ONIL without rings	Tier
High power thermal efficiency	%	15 ± 1	0	12 ± 1	0	8 ± 1	0	16 ± 3	0	19 ± 3	1	15 ± 2	1	21 ± 3	1
Low power specific consumption	MJ/min/L	0.2 ± 0.10		0.1 ± 0.1	1	0.1 ± 0.1	0	0.1 ± 0.1	1	0.1 ± 0.1	1	0.1 ± 0.1	2	0.1 ± 0.1	1
High power CO	g/MJd	34 ± 4	0	15 ± 9	1	25 ± 6	0	18 ± 2	0	7 ± 3	4	6 ± 3	4	16 ± 4	1
Low power CO	g/min/L	0.2 ± 0.11		0.1 ± 0.1	4	0.1 ± 0.1	4	0.1 ± 0.1	4	0.1 ± 0.1	4	0.1 ± 0.1	4	0.1 ± 0.1	2
High power PM _{2.5}	mg/MJd	3001 ± 0		923 ± 239	1	1268 ± 363	0	957 ± 147	1	925 ± 175	1	879 ± 370	1	1117 ± 217	0
Low power PM _{2.5}	mg/min/L	25 ± 6	0	5 ± 1	1	10 ± 3	0	6 ± 1	1	6 ± 2	1	5 ± 2	1	12 ± 11	0
Indoor emissions CO ^a	g/min	2.3 ± 0.80		0.1 ± 0.1	4	0.1 ± 0.1	4	0.1 ± 0.1	4	0.1 ± 0.1	4	0.1 ± 0.1	4	0.1 ± 0.1	4
Indoor emissions PM _{2.5} ^a	mg/min	212 ± 720		0.6 ± 0.2	4	0.7 ± 0.1	4	0.6 ± 0.1	4	0.8 ± 0.2	4	0.5 ± 0.1	4	0.9 ± 0.1	4

Note: Variability is expressed as ± standard deviation.

^a CO and PM_{2.5} indoor emissions were estimated assuming a locally measured average fugitive emissions value of 1% the total emissions.

Appendix B. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.deveng.2016.06.001>.

References

REMBIO, Red Mexicana de Bioenergía, Cuaderno Temático No. 4, LA BIOENERGÍA EN MÉXICO, Situación Actual y perspectivas, 2011.

V. Berrueta, I Seminario Taller Latinoamericano DE Cocinas/Estufas Limpias, Promoviendo La Adopción y Uso Sostenible En Gran Escala, Lima, Peru, 2014.

International Organization for Standardization, IWA 11:2012: Guidelines for Evaluating Cookstove Performance, Author, Geneva, Switzerland, retrieved from (http://www.iso.org/iso/catalogue_detail?csnumber=61975), 2012

Johnson, M.A., Chiang, R.A., 2015]. Quantitative stove use and ventilation guidance for behavior change strategies. *J. Health Commun. Int. Perspect.* 20 (Suppl.), S6–S9.

Johnson, M., Edwards, R., Morawska, L., Smith, K., Nicas, M., 2014]. Review 3: model for linking household energy use with indoor air quality, WHO Indoor Air Quality Guidelines: Household Fuel Combustion.

ISO IWA, International Standards Organization (ISO) International Workshop Agreement (IWA), ISO International Workshop on Cookstoves, (<http://www.pciaonline.org/proceedings>), 2012

Water Boiling Test (WBT) Version 4.1.2, Available from: Partnership for Clean Indoor Air, (http://www.pciaonline.org/files/WBT4.1.2_0_0.pdf) (accessed 2013 February).

Johnson, M., Edwards, R., Alatorre Frenk, C., Masera, O., 2008]. In-field greenhouse gas emissions from cookstoves in rural Mexican households. *Atmos. Environ.* 42, 1206–1222.

MacCarty, N., Still, D., Ogle, D., 2010]. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. *Energy Sustain. Dev.* 14, 161–171.

Jetter, J.J., Kariher, P., 2009]. Solid-fuel household cook stoves: characterization of performance and emissions. *Biomass Bioenergy* 33, 294–305.

MacCarty, N., Ogle, D., Still, D., Bond, T., Roden, C., 2008]. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. *Energy Sustain. Dev.* 12, 5–14.

Smith, K.R., Uma, R., Kishore, V.V.N., Lata, K., Joshi, V., Zhang, J., Rasmussen, R.A., Khalil, M.A.K., 2000]. Greenhouse Gases from Small-scale Combustion Devices in Developing Countries. EPA/600/R-00/052. U.S. Environmental Protection Agency, Washington, DC.

Zhang, J., Smith, K.R., Ma, Y., Ye, S., Jiang, F., Qi, W., Liu, P., Khalil, M.A.K., Rasmussen, R.A., Thorneloe, S.A., 2000]. Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors. *Atmos. Environ.* 34, 4537–4549.

Edwards, R., Smith, K.R., Zhang, J., Ma, Y., 2004]. Implications of changes in households stoves and fuel use in China. *Energy Policy* 32, 395–411.

Winter, J.C.F., 2013]. Using the Student's t-test with extremely small sample sizes. *Pract. Assess. Res. Eval.* 18 (10), 1–12.

Grimsby, L.K., Rajabu, H.M., Treiber, M.U., 2016]. Multiple biomass fuels and improved cook stoves from Tanzania assessed with the water boiling test. *Sustain. Energy Technol. Assess.* 14, 63–73.

Berrueta, V., Edwards, R., Masera, O.R., 2008]. Energy performance of woodburning cookstoves in Michoacan, Mexico. *Renew. Energy* 33 (5), 859–870.

Chung, A., Chang, D.P.Y., Kleeman, M.J., Cahill, T.A., Dutcher, D., McDougall, E.M., Stroud, K., 2001]. Comparison of real-time instruments used to monitor airborne particulate matter. *J. Air Waste Manag. Assoc.* 51, 109–120.

Ramachandran, G., Adgate, J.L., Hill, N., Sexton, K., Pratt, G.C., Bock, D., 2000]. Comparison of short-term variations (15 min averages) in outdoor and indoor PM_{2.5} concentrations. *J. Air Waste Manag. Assoc.* 50, 1157–1166.

Bailis, R., Berrueta, V., Chengappa, C., Dutta, K., Edwards, R., Masera, O., Still, D., Smith, K.R., 2007]. Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health project. *Energy Sustain. Dev.* 12 (2), 57–70.

Jetter, J., Zhao, Y., Smith, K.R., Khan, B., Yelverton, T., DeCarlo, P., Hays, M.D., 2012].

- Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards. *Environ. Sci. Technol.* 46, 10827–10834.
- Masera, O.R., Navia, J., 1997]. Fuel switching or multiple cooking fuels? Understanding inter-fuel substitution patterns in rural mexican households. *Biomass Bioenergy* 12 (5), 347–361.
- Chen, Y., Roden, C.A., Bond, T.C., 2012]. Characterizing biofuel combustion with patterns of real-time emission data (PaRTED). *Environ. Sci. Technol.* 46, 6110–6117 . <http://dx.doi.org/10.1021/es3003348>.
- Johnson, M., Edwards, R., Berrueta, V., Masera, O., 2010]. New approaches to performance testing of improved cookstoves. *Environ. Sci. Technol.* 44, 368–374.
- Edwards, R.D., Karnani, S., Fisher, E.M., Johnson, M., Naeher, L., Morawska, L., Smith, K.R., 2014]. Review 2: emissions of health-damaging pollutants from household stoves, WHO Indoor Air Quality Guidelines: Household Fuel Combustion.
- Johnson, M., Edwards, R., Ghilardi, A., Berrueta, V., Gillen, D., Alatorre Frenk, C., Masera, O., 2009]. Quantification of carbon savings from improved biomass cookstove projects. *Environ. Sci. Technol.* 43, 2456–2462.
- ISO TC 285, Clean Cookstoves and Clean cooking Solutions – Harmonized Laboratory Protocols – Part 1: Standard Test Sequence for Emissions and Performance, Safety and Durability, 2015.
- L’Orange, C., DeFoort, M., Willson, B., 2012]. Influence of testing parameters on biomass stove performance and development of an improved testing protocol. *Energy Sustain. Dev.* 16, 3–12.
- Makonese, T., Robinson, T., Pemberton-Pigott, C., Annegarn, H., 2011]. A preliminary comparison between the heterogeneous protocols and the water boiling test. *New Dawn Eng.*
- Yuntenwi, E.A.T., MacCarty, N., Still, D., Ertel, J., 2008]. Laboratory study of the effects of moisture content on heat transfer and combustion efficiency of three biomass cook stoves. *Energy Sustain. Dev.* 12 (2), 66–77.
- Adkins, E., Tyler, E., Wang, J., Siriri, D., Modi, V., 2010]. Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa. *Energy Sustain. Dev.* 14, 172–185.