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Closing the gap between lab and field cookstove tests: Benefits of multi-pot and sequencing cooking tasks through controlled burning cycles

Paulo Medina [a,*,1], V. Berrueta [b,2], M. Martínez [a,1], V. Ruiz [c,d,3,4], I. Ruiz-Mercado [c,e,3,5], O.R. Masera [c,3]

[a] *División de Estudios de Posgrado, Facultad de Ingeniería Química, Universidad Michoacana de San Nicolás de Hidalgo (UMSNH), Morelia, Michoacán, México*
[b] *Grupo Interdisciplinario de Tecnología Rural Apropiada A.C. (GIRA), Pátzcuaro, Michoacán, México*
[c] *Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México (UNAM), Morelia, Michoacán, México*
[d] *Facultad de Ingeniería, Universidad Nacional Autónoma de México (UNAM), Ciudad de México, México*
[e] *Consejo Nacional de Ciencia y Tecnología (CONACYT), Ciudad de México, México*

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ABSTRACT

There is a critical need for developing wood-burning cookstoves lab tests that better reflect their field performance, and that can be used to complement existing standard tests. This is particularly true for Plancha-type cookstove stoves, widely disseminated in Latin America, where existing tests, like Water Boiling Test (WBT) and Controlled Cooking Test (CCT), are either not well suited to these stoves or do not capture the simultaneous and sequential arrangement of local cooking practices –i.e., multi-pot cooking, pre-heating of meals, and use of residual heat. In this paper, we developed a "controlled cooking cycle" or "controlled burning cycle" (CBC) test to study the benefits, in terms of fuelwood and pollutants emissions savings, of multi-pot cooking arising from the integration of cooking tasks. Tests were conducted on the Patsari stove, a plancha-type stove that has been widely disseminated in Mexico and in other regions of Central America. We first used CCTs to evaluate the comparative energy and emissions performance of the Patsari stove relative to a traditional U-shaped open fire (U-type) for the most common cooking practices carried out in the Purepecha Region of Michoacan. We also compared results from the CBC multi-pot cooking with results from simply conducting the cooking tasks in series. All the CCTs and CBCs were carried out in a simulated kitchen at GIRA facilities in Patzcuaro, Michoacan, Mexico with two local cooks who performed all the cooking tasks in the traditional/typical manner of the region. Results from CCTs showed Patsari benefits relative to the open fires, in terms of fuelwood consumption and CO and $PM_{2.5}$ emissions savings, vary among cooking tasks and range from negligible to 63% depending on the parameter and the task. The sequential cooking and integration of these tasks in a CBC result in average savings of 65% for CO, 65% for $PM_{2.5}$ and 35% for fuelwood relative to the U-type, and of between 30% and 44% savings with respect to simply conducting the cooking tasks in series in the same stove. The CBC fuelwood savings obtained here are comparable with field results from Kitchen Performance Tests (KPT) conducted regionally by other authors. The results confirm that multi-pot cooking and a smart sequential integration of tasks developed by local users are key to achieve the maximum benefits from plancha-type stoves, and need to be much better reflected in standard lab tests.

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Introduction

Reliance on fuelwood for cooking and heating is very high in many Latin-American countries, particularly within rural areas. Wood is mostly burned in open fires, which require vast amounts of fuel and produce very high indoor air pollution (L'Orange et al., 2012), leading to several health effects (Rumchev et al., 2007), and environmental problems (Smith et al., 2010). To cope with this problem, plancha-type improved wood-burning cookstoves have been widely disseminated in several countries across North, Central and South-America such as Mexico, Bolivia, Peru and Honduras with >1 million stoves installed (I Seminario Taller Latinoamericano., 2014). In rural Mexico, the Patsari stove, a multi-pot

* Corresponding author at: División de Estudios de Posgrado, Facultad de Ingeniería Química, Universidad Michoacana de San Nicolás de Hidalgo (UMSNH). Gral. Francisco J. Mugica S/N, Ciudad Universitaria. Postal code: 58030. Morelia, Michoacán, México.
E-mail addresses: paulo491@hotmail.com (P. Medina), vberrueta@gira.org.mx (V. Berrueta), mcinco71@gmail.com (M. Martínez), victor_ruizgarcia@yahoo.com (V. Ruiz), ilse.ruiz@cieco.unam.mx (I. Ruiz-Mercado), omasera@gmail.com (O.R. Masera).
[1] **Postal addresses:** Gral. Francisco J. Mugica S/N, Ciudad Universitaria. Postal code: 58030. Morelia, Michoacán, México.
[2] **Postal addresses:** Carretera Pátzcuaro a Erongaricuaro 28. Postal code: 61613. Tzentzenguaro, Pátzcuaro, Michoacán, México.
[3] **Postal addresses:** Antigua Carretera a Pátzcuaro 8701, Ex-Hacienda de San José de la Huerta. Postal code: 58190. Morelia, Michoacán, México.
[4] **Postal addresses:** Avenida Universidad 3000, Ciudad Universitaria. Postal code: 04510. Ciudad de México, México.
[5] **Postal addresses:** Avenida de los Insurgentes Sur 1582, Crédito Constructor, Benito Juárez. Postal code: 03940. Ciudad de México, México.

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Fig. 1. A. Stoves tested. Left to right: Patsari stove and the U-type. B. Different in-field simultaneous cooking of several dishes on Patsari stoves observed in Purepecha Region of Central Mexico.

plancha-type stove,[6] has been well accepted due to its effectiveness to cook tortillas, but also is used to cook beans and rice, heat beverages, and to fry eggs as reported by Ruiz-Mercado and Masera, (2015).

Many studies have emphasized the need to develop standard lab and field tests that better reflect in-field conditions (Arora and Jain, 2015; Adkins et al., 2010; Bailis et al., 2007). This is particularly true for Plancha-type cookstove stoves, because Water Boiling Tests (WBT) are not well suited to these stoves, as a large fraction of the heat that is transmitted through the "plancha" is not captured by the pot filled with water that is placed on top of it. Adaptations to the standard Water Boiling Tests (WBT) such as the "*comal-olla*" or *"plancha-olla"* (Medina et al., 2017; ISO TC 285., 2015) or the "Mylar pot" (ISO TC 285., 2015) have been proposed to better estimate the actual heat transfer from the combustion of fuel to the plancha (Medina et al., 2017). But these adaptations, while important to have more realistic estimates of the stoves actual energy efficiency, are not aimed at giving feedback on their in-field performance.

Controlled Cooking Tests (CCT) were developed to give more insights on the stoves performance for the most relevant cooking practices within a region (Bailis et al., 2007). While CCTs have proved very valuable –and have not been used to the extent they should as a complement to WBT- they also present shortcomings. In fact, evidence from the field shows that local cooking tasks more than being a simple collection of isolated events, are usually performed following specific arrangements, which can be thought as daily "burning cycles "-or "cooking cycles"- (Johnson et al., 2010).

Here we argue that the combination of specific cooking practices carried out locally as well as the simultaneous and sequential arrangement of these practices in burning cycles –i.e., multi-pot cooking, and use of residual heat for pre-heating meals and water, or for keeping food warm, see (Ruiz-Mercado and Masera, 2015), could be used as a starting point for developing new standard tests that could help to better assess the actual field performance of improved stoves. These tests, simulating regional cooking cycles, can be viewed as a complement to standard tests, such as WBT and individual CCTs.

To test these hypotheses, we first conducted a series of CCTs for the most common meals (or cooking tasks) prepared in the Purepecha Highlands, Central Mexico and compared the relative performance of Patsari improved stoves to traditional open fires for each task. We then integrated the different cooking tasks in a Controlled Burning Cycle (CBC) and re- assessed the energy and emissions performance of Patsari stove relative to both traditional open fires and to itself for the whole cycle and for a theoretical cycle consisting of the simple additions of conducting the individual tasks in series.

Methods

Controlled Cooking Test

Stoves. Fig. 1A shows the cookstoves tested: Patsari stove and a traditional fire: the U-shaped open fire (U-type). **Patsari:** the body of Patsari

[6] Plancha-type stoves are characterized for having a large flat griddle, named "plancha" or "comal" that covers the upper part of the stove, avoiding the direct contact between the fire and the pot and also allowing the smoke to exit the house through a chimney. The griddle is usually made of metal, and the stoves could be metallic or made of local materials, like bricks, mud, and cement.

stove is made of brick and cement with a combustion chamber, a main metal comal that is 52 cm in diameter, two secondary comales that are 27 cm in diameter and a chimney to release the pollutant gases outside the cooking area. **U-type:** Masonry (e.g., bricks, stones, mud) materials fire encloses the fire simulating a U-shaped combustion chamber (Masera et al., 2007). Patsari stove was tested against U-type to evaluate five typical meals and a CBC. ***Performance test.*** CCT protocol version 2.0 (Controlled Cooking Test, CCT, 2015) was used to determine both performance and emissions parameters of wood-burning cookstoves. White oak (*Quercus bicolor*) was used in all CCT and CBC tests, the average dimensions of fuel were 3 cm × 5 cm × 30 cm, and a digital scale with 1 g resolution was used to determine fuelwood measurements. Fuel moisture content was measured with a Protimeter Timbermaster Wood Moisture Meter as reported by Pennise et al. (2010), and the average fuelwood moisture content for all CCT tests was 10 ± 2%, expressed as wet basis with a range of (7–15%). All CCT and CBC tests were initiated with a small amount (~25 g) of "ocote" that is a highly resinous piece of pitch pine used as a fire starter material. ***Location.*** All the CCTs and CBCs were carried out in a simulated kitchen at GIRA facilities in Patzcuaro, Michoacan, Mexico. The simulated kitchen has the following internal dimensions: 2.9 m wide by 3.85 m in length, with a height of 3.2 m. ***Cooks.*** Two local cooks were hired to perform all the cooking tasks in the traditional/typical method familiar to them (see Table A3). ***Individual meals.*** As mentioned before, five items were prepared on the Patsari and U-type stoves: 3 kg of tortillas, fried eggs (5 pieces), ½ kg of fried rice, ½ kg of fried boil beans, and 1 L of boiled water. Each individual task was performed in the main comal of the Patsari stove and a similar metal comal, which is 52 cm in diameter (see Fig. 1A), was used in the U-type to perform all the individual tasks. It is important to note that in the Purepecha Region of Michoacan a metal or clay comal is used over the open fire to prepare tortillas as well as other food items (Berrueta et al., 2008; see Fig. A4). ***Cooking cycle.*** The CBC was designed to mimic the way Patsari users cook their meals in terms of the time sequence of meals and the way each dish is accommodated in the different comales (for example, skilled users make use of the residual heat of the secondary comales to warm up water or to slow cook some meals) as reported by (Ruiz-Mercado and Masera, 2015). It was performed in Patsari and U-type. CBC included 3 kg of tortillas, fried eggs (5 pieces), ½ kg of fried rice, ½ kg of fried boil beans, and 1 L of boiled water. The cooking procedure was: 1) to make tortillas and 2) to fry rice, to fry beans and to boil water simultaneously on the main Patsari comal and to fry 5 eggs on the secondary comal. These cooking tasks are typical from the Purepecha region as reported by (Masera and Navia, 1997). A similar CBC was applied in the U-type fire using the metal comal mentioned previously to perform the cooking cycle. In this case tortillas were made first, frying beans, frying rice and boiling water were done simultaneously using the metal comal, and then the 5 eggs were fried. The cooking cycle was established based on extensive field work in the area and detailed visits to 30 households, where the main cooking tasks, sequences and timing of these practices were documented. Fig. 1B shows typical arrangements of multiple dishes in Patsari stoves installed in the Purepecha Region.

Appendix A reports the following supplementary material: Patsari stove performance relative to U-type, Patsari performance across different comparison levels, numbers of tests by individual tasks and for the CBC and a series of Figures to show: 1) the simulated kitchen, 2) CBC's simultaneous arrangement, 3) experimental setup to capture emissions and 4) use of the comal over the open fire by Michoacan rural users. Appendix B shows a detailed description for the CBC including equipment, testing procedure and calculations.

Emission measurement

Fine particulate matter ($PM_{2.5}$) emissions samples were collected using a portable hood, as shown in Fig. A3, that is made of fire resistance fabric, measuring 1 m × 1 m, and with a metal fan to exhaust emissions. To collect CO_2 and CO emissions a Flue Gas Analyzer (FGA) (Autologic, USA) was used that measures gas concentrations directly from the flue (Prapas et al., 2014; Tsai et al., 2003). Patsari emission samples were collected from probes inserted 40 cm, 50 cm and 60 cm above the chimney base. Open fire emissions were taken with an "Araña probe" (Roden et al., 2006) or "3-pronged probe" (Johnson et al., 2009) about 1.5 m above the open fire as reported by Roden et al. (2009). FGA was calibrated using CO and CO_2 reference gas as reported by Johnson et al. (2009), and continuous measurements were recorded every 8 s.

$PM_{2.5}$ emissions were measured using gravimetric methods as reported by Jetter and Kariher, (2009). Integrated $PM_{2.5}$ samples were collected using a GAST Vacuum Pump (Gast Manufacturing Inc.) at a flow rate of 16.7 L per minute. $PM_{2.5}$ was collected on FPAE-102 glass fiber filters (4 in. 1 μm pore size, HI-Q Environmental Products; San Diego, CA) which were placed inside the filter holder (ILPH-102, HI-Q Environmental Products; San Diego, CA) that was positioned downstream of a $PM_{2.5}$ cyclone (URG-2000-30EHS, URG; Chapel Hill, NC). Filters were equilibrated in a temperature- and humidity-controlled room for at least 24 h (Li et al., 2012) and then weighed pre-and post sampling using a microbalance (0.01 mg readability, CX 265; Citizen Scale India Private Limited).

Statistical analysis

The Patsari stove and both open fires were tested for significant differences in performance and emissions parameters. A statistical analysis of difference in means was conducted with a two sample *t*-test. The probability of error of 1%, 5% and 10%, was considered significant (Beyene et al., 2015).

Results

Technical Performance and Emissions Characteristics of Individual Cooking Tasks

Table 1 shows the performance parameters associated to each individual cooking task for both the Patsari stove and U-type in terms of total fuelwood consumed, energy consumed, cooking time and CO and $PM_{2.5}$ total emissions. Results are presented as averages ± one standard deviation. For the U-type, total fuel consumption varied by a factor of 4 between tasks. Also, the energy consumed per mass of food cooked varied by a factor of 5 among tasks, ranging from 12 ± 1 MJ/kg for tortillas to 65 ± 10 MJ/kg for frying eggs. Additionally, cooking times varied by a factor of 3, ranging from a bit >20 min for frying eggs, frying beans, and boiling water to one hour (61 ± 14 min) to cook fried rice.

For the Patsari stoves, fuel use also ranged by a factor of ~4. The energy consumption per unit of food cooked for making tortillas for the Patsari was the lowest with 9 ± 1 MJ/kg, which is in a good agreement with the value reported by Berrueta et al. (2008), and went up to 30 ± 3 MJ/kg for frying eggs. There are no significant differences, in terms of energy consumed, for Patsari stove and U-type for boiled water, fried rice and fried beans tasks, while these differences were significant for tortilla making and for fried eggs. Cooking time for the Patsari stove varied by a factor of 3, ranging from 19 ± 6 min for frying eggs, to almost one hour (57 ± 8 min) to prepare fried rice.

Total $PM_{2.5}$ and CO emissions for the U-type fire varied approximately 6-fold among cooking tasks ranging from 2.3 ± 0.5 g and 25 ± 5 g, respectively, for frying beans to 15 ± 3 g and 126 ± 36 g, respectively, for preparing rice. Total emissions for the Patsari stove were significantly smaller than the U-type for most of the tasks, ranging from 1.1 ± 0.4 g and 14 ± 5 g, respectively, for frying eggs, to 6 ± 1 g and 65 ± 14 g, respectively, for frying rice. CO and $PM_{2.5}$ emission factors per kg of dry fuelwood for Patsari stove were also statistically different from those estimated for U-type for tortillas, fried eggs and fried rice (see Table 1).

Table 1
Comparative Performance and emissions parameters for Patsari and U-type stoves for individual cooking tasks measured with Controlled Cooking Tests.

Task	Stove	N	Fuelwood consumption	Energy consumed[a]	Cooking time	Total emissions		Emission factors[b]	
			g	MJ/kg	min	gCO	$gPM_{2.5}$	gCO/kg	$gPM_{2.5}$/kg
Tortillas	Patsari	6	1281 ± 139	9 ± 1	51 ± 6	60 ± 7	2.5 ± 0.5	47 ± 2	1.7 ± 0.3
	U-type	6	1829 ± 117	12 ± 1	45 ± 6	115 ± 33	4.4 ± 1.0	62 ± 14	3.0 ± 0.7
	p-value		< 0.01***	< 0.01***	0.13	0.01***	0.01***	0.05**	0.01***
Fried eggs	Patsari	6	438 ± 30	30 ± 3	19 ± 6	14 ± 5	1.1 ± 0.4	32 ± 11	0.8 ± 0.3
	U-type	6	872 ± 73	65 ± 12	21 ± 8	38 ± 14	2.9 ± 2.0	43 ± 16	2.0 ± 1.4
	p-value		< 0.01***	< 0.01***	0.62	0.02**	0.08*	< 0.01***	0.07*
Fried rice	Patsari	3	1626 ± 201	14 ± 1	57 ± 8	65 ± 14	6 ± 1	33 ± 14	4.4 ± 0.9
	U-type	3	2728 ± 480	19 ± 6	61 ± 14	126 ± 36	15 ± 3	53 ± 13	7.2 ± 4.6
	p-value		0.04**	0.04**	0.65	0.09*	0.08*	0.07*	0.08*
Fried beans	Patsari	3	688 ± 182	20 ± 7	28 ± 14	20 ± 18	2.2 ± 0.9	20 ± 20	0.8 ± 0.7
	U-type	3	750 ± 139	23 ± 7	21 ± 3	25 ± 5	2.3 ± 0.5	33 ± 6	3.0 ± 2.6
	p-value		0.67	0.64	0.03**	0.66	0.42	0.48	0.42
Boil 1 L of water	Patsari	3	920 ± 173	16 ± 2	30 ± 9	33 ± 12	3.6 ± 1.2	35 ± 6	2.5 ± 0.8
	U-type	3	1092 ± 54	18 ± 1	24 ± 6	44 ± 3	5.0 ± 1.1	41 ± 1	3.4 ± 0.7
	p-value		0.22	0.21	0.06*	0.23	0.21	0.28	0.21

Notes: Values shown are averages ± standard deviation. Patsari stove values were tested against U-type using a t-distribution with ***α = 0.01, **α = 0.05 and *α = 0.10.
[a] We use 20 MJ/kg and 28 MJ/kg as the heating value of wood and charcoal, respectively as reported by Berrueta et al. (2008) and Masera et al. (2005).
[b] CO and $PM_{2.5}$ emission factors are expressed as gram of pollutant per kg of dry fuelwood.

Relative performance of Patsari stove against the U-type fire for Individual Tasks

Fig. 2 shows fuelwood, cooking time and emissions savings for Patsari stove relative to U-type for each individual meal. Significant savings in fuelwood consumptions of between 30% to 50% were obtained for fried eggs, fried rice, and for making tortillas. For CO total emissions, Patsari stove presented significant savings for tortillas, fried eggs and fried rice with 48% ($p = 0.01$, $\alpha = 0.01$), 63% ($p = 0.02$, $\alpha = 0.05$) and 48% ($p = 0.09$, $\alpha = 0.10$), respectively. For $PM_{2.5}$ emissions, savings were observed to be significant for tortilla making ($p = 0.01$, $\alpha = 0.01$), fried eggs ($p = 0.08$, $\alpha = 0.10$) and fried rice ($p = 0.08$, $\alpha = 0.10$). There was not significant CO and $PM_{2.5}$ emissions difference for Patsari and open fire for boiling water and fried beans. Although open fire seems to be faster, differences in terms of cooking time were not statistically significant (i.e. $p > 0.10$) for tortillas, fried eggs and fried rice between Patsari and U-type. Table A1 shows Patsari performance relative to U-type in terms of percentage reduction and *p*-values for all individual cooking tasks.

Percentage savings for Patsari stove were estimated: $\left[\frac{(parameter(open\ fire)-parameter(Patsari))}{parameter(open\ fire)}\right]^{*}100\%$ as reported by Adkins et al. (2010).

Energy and emissions performance for CBC

Table 2 shows performance parameters and emissions contribution for the Patsari and U-type for the CBC. Average emissions savings for Patsari stove reached 65% ($p \leq 0.01$, $\alpha = 0.01$) for both CO and $PM_{2.5}$ relative to U-type. Average fuelwood savings for Patsari stove were 35% ($p < 0.01$, $\alpha = 0.01$). No significant differences were observed for cooking time between Patsari stove and U-type (i.e. $p > 0.10$) The average modified combustion efficiency (MCE) for Patsari stove during CBC was 96 ± 1% which is statistically different ($p < 0.01$, $\alpha = 0.01$) from 92 ± 1% for the U-type. Emission factors, expressed in g carbon of pollutant per kg dry wood, for CO and $PM_{2.5}$ for Patsari during CBC were 20 ± 3 g(c)CO/kg and 1.5 ± 0.9 g(c)$PM_{2.5}$/kg, respectively, which are comparable to those reported by Johnson et al. (2008) for a normal

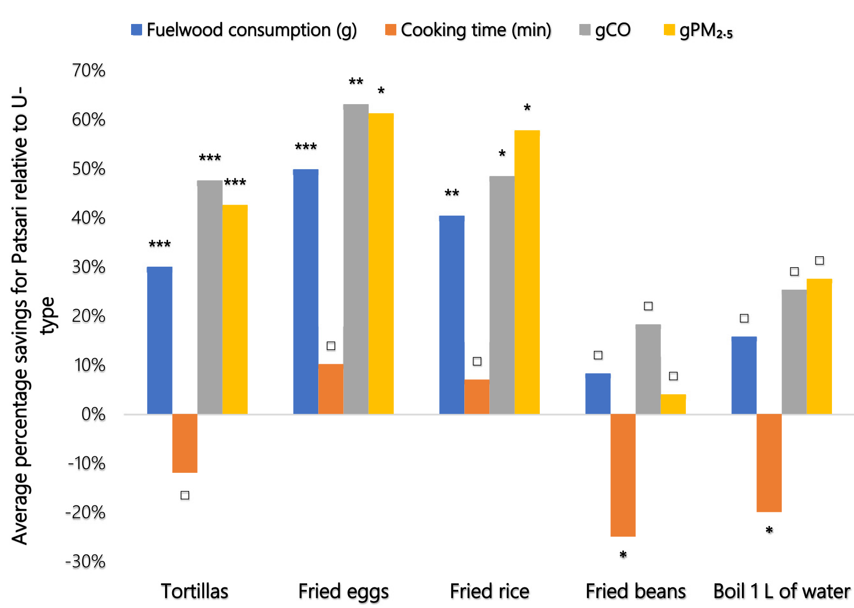

Fig. 2. Fuelwood, cooking time and emissions savings for Patsari stove relative to U-type. *Notes*: Bars marked with ***, ** and * indicate significant at 1%, 5% and 10% levels, respectively. □ means not significant (i.e. $p > 0.10$).

Table 2
Comparative performance and emissions metrics for Patsari and U-type for the CBC cooking cycle.

Task	Stove	N	Fuelwood consumption	Energy consumed	Cooking time	Total emissions		Emission factors		MCE
			g	MJ/kg	min	gCO	$gPM_{2.5}$	g(c)CO/kg	$g(c)PM_{2.5}$/kg	%
CBC	Patsari	5	3066 ± 276	9 ± 1	110 ± 17	143 ± 34	9 ± 2	20 ± 3	1.5 ± 0.9	96 ± 1
	U-type	5	4718 ± 463	13 ± 1	103 ± 12	408 ± 82	26 ± 8	30 ± 5	5.5 ± 1.6	92 ± 1
p-value			$< 0.01^{***}$	$< 0.01^{***}$	0.52	$< 0.01^{***}$	0.01^{***}	0.01^{***}	0.03^{**}	$< 0.01^{***}$

Notes: Values shown are averages ± standard deviation. Patsari stove was tested against U-type using a t-distribution with $^{***}\alpha = 0.01$ and $^{**}\alpha = 0.05$.

cooking day in a rural household. Fig. 3 shows the MCEs time dynamics for Patsari and U-type during the CBC. While Patsari stove shows MCEs higher or equal than 0.95 75% of the time, U-type exceeded 0.95 only 22% of the total cooking time. These results are comparable with a real burning cooking cycle reported by Johnson et al. (2010).

Cooking cycle relative to individual tasks sum for the Patsari stove

To understand the benefits of multi-pot cooking and of a smart sequencing of the different cooking tasks, Fig. 4 compares the relative performance of the Patsari stove when completing the CBC burning cycle vs the values resulting from conducting the individual tasks in series. Results showed average fuelwood and cooking time savings of 38% ($p < 0.01$, $\alpha = 0.01$) and of 41% ($p < 0.01$, $\alpha = 0.01$) for the CBC. In addition, total emissions savings for CO and $PM_{2.5}$ of 30% ($p = 0.01$, $\alpha = 0.01$) and 44% ($p < 0.01$, $\alpha = 0.01$), respectively, were also obtained. Table A2 shows average values for fuelwood consumption, cooking time and CO and $PM_{2.5}$ total emissions for this comparison.

Discussion

CCT for Individual Meals

Cooking tasks vary in terms of the time, energy, emissions and power needed to be completed using traditional open fires. The benefits from adopting Patsari stoves also differ by individual cooking tasks in terms of performance parameters and emissions contribution. In general, for tortilla making, fried eggs and fried rice the Patsari stove outperformed the U-type showing substantial energy and CO and $PM_{2.5}$ emissions savings. The possible explanation in these cases is the effective use of the stove cooking power as reported by Jetter et al. (2012). Most of the $PM_{2.5}$ emissions occur at start-up combustion process (MacCarty et al., 2008) which explains the relatively larger emission contribution of the short-time tasks compared to longer-time tasks. Overall, while the U-type was faster than Patsari stove, the differences in cooking time were not statistically significant for tortillas, fried eggs and rice soup.

Cooking cycle

When the meals were cooked following local user's practices, i.e., making the most out of the main and secondary comales and of the sequencing of cooking tasks, significant fuelwood savings for Patsari stove relative to U-type were observed. These savings result from an improved overall heat transfer to the water and foods by cooking more than one dish at a time and by using the secondary comales to pre-heat some of the items. The Patsari had substantial emissions savings relative to the U-type fire, which result from a cleaner combustion and from burning less fuel (Medina et al., 2017). Results for the evolution of real-time MCE confirmed this statement, showing that the Patsari stove achieved 75% of the time a MCE higher or equal than 95% even though the cooking cycle is characterized by complex burn events as reported by Johnson et al. (2010). Not surprisingly real-time MCEs for the open fire were extremely irregular likely due to inconsistent combustion conditions (air-to-fuel ratio, mixing, temperature, residence time, etc.)

Also to be noted are the differences between the CBC and the conducting of individual tasks in series for the Patsari stove. This shows first, the benefits of multi-pot cooking, which allows making the most of the heat delivered by the stove in the main and secondary comales, and second, a wise integration of fast and slow tasks developed by local users, that optimizes fuel use. Finally, an additional interesting result from CBC tests is that the fuel savings obtained by Patsari stove relative to open fires (such as the U-type fire) are similar to the savings reported in the field using Kitchen Performance Tests (KPTs). For example, Miranda (2015) in a review of regional KPTs conducted before and after families adopted Patsari stoves found that they save approximately 40% fuelwood relative to open fires, a figure that is in good agreement with the average 35% savings for the CBC found in this study.

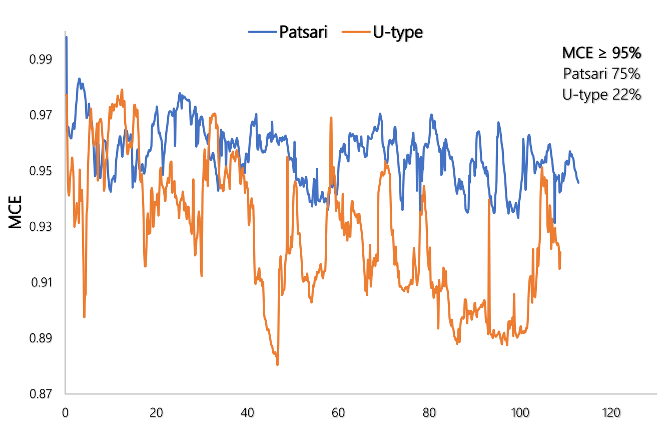

Fig. 3. Time evolution of MCE for Patsari stove and U-type for CBC. *Note:* MCEs averaged over 5 repeats for Patsari and U-type are shown.

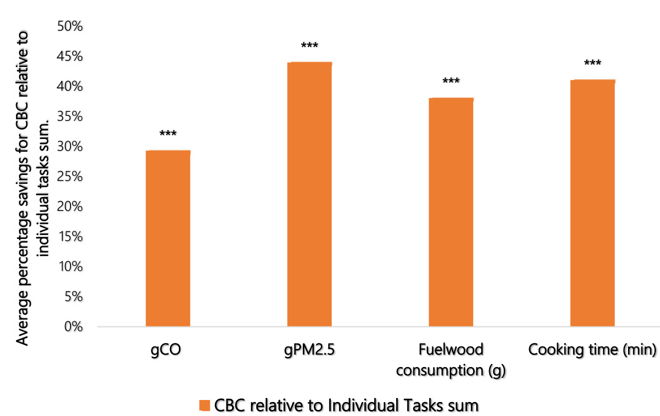

Fig. 4. Benefits of CBC vs the conducting of cooking tasks in series for the Patsari stove. *Notes:* Bars marked with *** were found to be significant at $\alpha = 0.01$. The sum of Individual tasks for Patsari stove was estimated: $\sum(parameter_{tortillas} + parameter_{fried\ eggs} + parameter_{fried\ rice} + parameter_{fried\ beans} + parameter_{boil\ 1\ L\ of\ water})$.

Conclusions

The present study proposed a "controlled burning cycle" (CBC) test as a first step to the development of new standard lab tests that should better represent in-field stove performance for specific regional contexts.

Performing a series of CCT for a representative set of daily meals, we found that the relative advantages of Patsari stoves against traditional open fires differ by cooking task in terms of energy demand, cooking time and CO and $PM_{2.5}$ emissions. Mimicking the cooking strategies followed by skilled Patsari users in the field by means of the CBC test, we found that simultaneous cooking of different dishes and the smart sequencing of cooking tasks help to virtually eliminate the disadvantages of Patsari stoves against the open fires. The CBC test also helped confirm that when operating Patsari stoves in cooking cycles very significant fuelwood, total CO and $PM_{2.5}$ emissions and cooking time savings are achieved compared to conducting individual cooking tasks in series in the same stove. Finally, we found that fuelwood savings for Patsari plancha-type stoves during CBC were comparable with in-field measurements of Patsari stoves conducted previously in the same Region.

As no standard test currently tackles two of the main plancha stoves users´ perceived benefits, i.e., the ability to cook several dishes at a time with different power and time requirements, and the ability to use residual heat –thus saving time and fuel- through the smart sequencing of cooking tasks, we think that the CBC presented here is worth pursuing and holds promise for the development of lab tests that better inform about the likely in-field performance of multi-pot and plancha stoves at the regional level. The CBC could then be integrated into a portfolio of standard tests that, together with existing tests such as WBTs, CCTs and KPTs, could provide a more robust understanding of the stove lab and in-field performance.

Several challenges remain that need to be tackled for CBC to be adopted as standard protocol. On the one hand, in its present form, the CBC test is representative of a cooking cycle from the Purepecha Region of Central Mexico. Specific cooking cycles should be developed for other regions as, that accurately represent their diversity of dishes, techniques and practices. Also, the CBC has been performed so far only in the Patsari stove. It is important to test it in other plancha stoves that have also been widely disseminated in Mexico and Central America. Finally, more detailed information about the exact sequencing of dishes, the influence of different cooks in overall variability of results, and other factors should be gathered to convert the CBC into a truly standard protocol.

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Appendix A. Supplementary data

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