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Original article

Fuzzy interval propagation of uncertainties in experimental analysis for improved and traditional three – Stone fire cookstoves

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ABSTRACT

The performance indicators of Improved Cook Stoves (ICSs) for Developing Countries are commonly evaluated and compared using the arithmetic average of replicated tests performed using a standardized laboratory-based test, commonly the Water Boiling Test (WBT).

Possibility theory is here employed to examine energy data retrieved from the WBT-based literature regarding the results of laboratory tests on ICSs and traditional Three-Stone Fire (TSF) stoves; fifty-seven comparisons of stoves are analysed. Chebyshev and uniform possibility distributions are employed to represent energy data affected by epistemic uncertainty. The extension principle of fuzzy set theory is applied to obtain possibility distributions of the *saving of fuel use* parameter for each comparison of cookstoves. The results indicate that at 90%, 95% and 99% degree of confidence, only 22.22%, 15.00% and 15.00% of all the supposed "improved" stoves emerged respectively as real ICSs at most, while the percentage of "improved" stoves obtained by considering the mean values of the WBT is among 3 and 6 times higher than the percentage resulted by taking into account the epistemic uncertainties. The work suggests how neglecting intrinsic uncertainties of tests' results might lead to misinterpret and report non-comprehensive information about ICSs' thermal energy performance, and to reveal some concerns about their effective improvements over traditional devices.

Introduction

As indicated in the World Energy Outlook 2015 [1], due to the lack of access to clean and efficient cooking facilities, almost 2.7 billion people in Developing Countries (DCs) rely on traditional biomass and three-stone fire (TSF) cookstoves to meet their cooking needs (Fig. 1a). In this context, gases and particulate matter produced by incomplete combustion of solid fuels burnt in low-efficiency traditional cookstoves cause over 4 million deaths per year [2], due to chronic obstructive pulmonary and ischemic heart diseases.

To mitigate the aforementioned problem, an immediate shift from traditional to modern and clean fuels and cooking appliances is not always feasible. Therefore, the introduction of improved biomass-fuelled systems, namely Improved Cook Stoves (ICSs), is supposed to be necessary, since they are considered substantially more efficient than traditional cookstoves (Fig. 1b), reducing pollutant emissions and wood consumption.

Numerous international Institutions, like the Global Alliance for Clean Cookstoves (GACC), research centres and private manufacturers of firewood cookstoves are involved in international programmes of promotion of ICSs all over the world – 28 million devices have been disseminated by the GACC's partners until 2014 [3]. In parallel, laboratory protocols for testing ICSs have been developed by research centres and international organisations in order to provide a homogenous and unique methodology for testing the stoves and reporting the performances. The most widely recognized is the Water Boiling Test (WBT), developed originally between 1982 and 1985 by the Volunteers in Technical Assistance (VITA) [4]. The WBT is currently referenced by GACC for evaluating and comparing stoves' performances and it is used for assessing the Climate Impacts of Cookstove Projects within the Clean Development Mechanism of carbon-market [5]. However, different authors have been raising doubts about the consistency of WBT results, focusing in particular on three issues: (i) L'Orange et al. [6] highlighted the role of thermodynamic uncertainties (*viz.* variable steam production and boiling point determination) on results repeatability; (ii) Zhang et al. [7] raised questions about the rationale of some calculations and about metrics terminology; (iii) finally, Wang et al. [8] criticised the statistical approach recommended by this standardised laboratory-based test to evaluate,

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Nomenclature

e	energy use [MJ]
E_{II}	secondary energy [MJ]
E_I	primary energy [MJ]
EF	emission factor [g/kg]
LHV	lower heating value [MJ/kg]
m_{wood}	mass of wood [kg]
t_b	time to boil [min]
ε	savings of fuel use [%]
η	thermal efficiency [–]
π	possibility distribution

Acronyms – subscripts

CO	Carbon Monoxide
CO_2	Carbon Dioxide
cs	Cold Start
DC	Developing Country
hs	Hot Start
ICS	Improved Cook Stove
ISO	International Organization for Standardization
GACC	Global Alliance for Clean Cookstoves
PCIA	Partnership for Clean Indoor Air
PM	Particulate Matter
SD	Standard Deviation
TEG	Thermoelectric Generator
TSF	Three-Stone Fire
VITA	Volunteers In Technical Assistance
WBT	Water Boiling Test

Fig. 1. Examples of TSF (*a*) and ICS (Rocket model) (*b*).

communicate and compare performances and emissions of tested stoves, *i.e.* using the arithmetic average of three replicate tests.

These doubts related to the WBT structure moved the authors of this work to review the scientific literature regarding laboratory tests on ICSs, and to adopt appropriate statistical methods to critically examine the WBT-based data collected in the review, which concern the performances of cookstoves. Three different approaches have firstly been taken into consideration. The *purely probabilistic* approach is usually employed to represent the uncertainties related to all the parameters of a mathematical model, which describe some real phenomena, by single probability distributions [9]. This approach is commonly adopted to represent precise observations affected by variability [10], and it is the approach indicated in the statistical section of the WBT protocol [11], which suggests representing the uncertainties related to test results through *t-student* probabilistic distributions to draw statistical inferences at 95% confidence level. However, uncertainties cannot be always objectively quantified, especially when they are reported in the form of confidence intervals based on the experience and intuition of who estimates the numerical values of such uncertain parameters (*i.e.* expert judgment), or affected by imprecision due to systematic measurement errors [9]. In this context, the use of probability distribution to express incomplete knowledge and "epistemic uncertainty" is questionable. Baudrit et al. [9] state this concept and the need to consider different approaches with this consideration: «when an expert gives his/her opinion on a parameter by claiming: "I only know that the value of x lies in an interval *A*", the uniform probability with support A is used. This choice introduces information that in fact is not available and may seriously bias the outcome of risk analysis in a non-conservative manner [12]». This is because the adoption of a uniform distribution may mean the expert is totally aware that the value of the underlying parameter is really random in the interval *A*, or simply (s)he lacks in precise information. Therefore, to isolate a single probability distribution in the domain of each parameter may be misleading. More faithful representations of imprecise knowledge of parameters and phenomena exist. The *evidence theory*, introduced by Arthur P. Dempster and developed by Glenn Shafer in 1976 [13], provides mathematical tools to analyse phenomena affected by imprecision (e.g. systematic errors of a measurement apparatus) and variability (e.g. random errors) at the same time. The *numerical possibility theory* described by Zadeh in 1978 [14] is usually employed when available knowledge on parameters is often imprecise, vague or incomplete [9,10]. The approach is based on the introduction of the possibility distribution π – also viewed as a nested set of confidence intervals, namely fuzzy sets –, which expresses the family of all probability distributions with support in a given interval A [15].

When dealing with cookstoves' performances evaluation, imprecise knowledge is the main source of epistemic uncertainties, which arise from WBT results. As a matter of fact, a low number of test replicates may be the source of two main uncertainties. Firstly, the use of t-student distribution, as recommended in the statistical section of the WBT protocol, should be verified through the hypothesis of Gaussian distribution of data, and related methodologies may be less accurate for small sample size [16]. Kolmogorov-Smirnov [17] and Shapiro–Wilk [18] are valuable tests for the assessment of normality, but their application for evaluating the Gaussian distribution of small samples may by biased by the fact that small samples most often pass normality tests, while increasing the sample size, «significant results (*viz.* the rejection of the null hypothesis of normal distribution) would be derived even in the case of a small deviation from normality» [19]. Secondly, as Wang et al. [8] indicate, the value of variance obtained from a very small number of replicates may considerably underestimate the variance that could be obtained by increasing the sample, biasing eventual statistical inferences. We therefore drew upon the possibility theory for uncertainty analysis and we employed the extension principle of fuzzy set theory to propagate uncertainties of data retrieved from the review. Following this approach, we were able to take into account the epistemic uncertainties originated by few test replicates and the unknown probabilistic distribution of data sample.

We limited our analysis to assess the energy performances of cooking devices, without considering pollutant emissions; therefore, given the specific focus of our work and being aware of the countless and extended definitions of "Improved Cookstove", we here refer to an ICS as a different stove from the TSF, which should reveal better thermal energy performances thanks to a closed combustion chamber[1].

The analysis performed in this paper contributes to assess ICSs technologies by proposing a reliable and robust statistical method, and by investigating how neglecting the epistemic statistical uncertainties originated from laboratory tests may lead to misinterpreted energy performance evaluations of such devices.

Section 'The WBT: metrics and outputs' includes references to the WBT metrics and main outputs. Section 'Data from the literature' reports a brief review of data collected from the scientific and grey literature concerning WBT-based energy comparisons among ICSs and traditional stoves. Section 'Uncertainty analysis performed' includes an overview on the possibility theory for uncertainty analysis and the extension principle of fuzzy set theory, as well as the application of those methods in our analysis on data found in the literature. Section 'Results and discussion' reports the results and a discussion of the analysis.

Material and methods

The WBT: metrics and outputs

WBT is the most well-known recognised procedure for ICSs testing. The most recent version of the protocol is named WBT 4.2.3, last revised in 2014 [11]. It is the result of a long process of updating and reviewing from different research groups, since its first release in 1985 by VITA. The WBT is a reference for the development of the interim international guidelines for stove performance by the International Organization for Standardization (ISO), as recognised during the ISO International Workshop Agreement held on February 2012 [20]. The current WBT version is composed of three phases:

1. *cold-start (cs)*: the stove is at room temperature and a measured quantity of water (2.5 or 5 L) is heated to the boiling;
2. *hot-start (hs)*: this second phase immediately follows the first one, while the stove is still hot. Water heated during *cs* phase has to be replaced with the same quantity of fresh cold water at the room starting temperature. Again the water is heated to the boiling in a standard pot;
3. *simmering*: the third phase continues immediately from the second one and it consists of simmering a measured amount of water at just below the boiling temperature for 45 min.

Regarding the number of replicates for testing a single stove, the protocol imposes only a minimum number of three replicates for ensuring results reliability. At the same time, it also specifies that three replicates are not necessarily sufficient to determine a stove performance within a certain confidence interval. Nevertheless, a great majority of published studies reports the results obtained with three or fewer WBT-replicates, as reported by Wang et al. [8], who suggest that this may be due to a misinterpretation of the Appendix 5 message «at least three tests should be performed on each stove» as "only three tests are needed" [8], regardless of variability and confidence interval. Wang et al. [8] investigated this topic, suggesting on a simplified version of WBT 3.0 how the minimum number of replicates to obtain a confidence interval of 95% for some indicators of performance is likely greater than five. Moreover, they demonstrated how the minimum statistically significant number of replicates could be even greater than five when comparing performances of two stoves.

Following the protocol, a complete assessment of a stove is performed through the evaluation of a number of performance metrics for each of the three phases, even though their general formulation is kept uniform throughout the test, with only slight differences in a few indicators. Three of the key indicators evaluated for all the 3 phases are *Thermal Efficiency* (η), *Emission factors (EF)*, *Time to boil* (t_b). Based on the recommendation of the protocol, it is worth noting that all the parameters evaluated through the WBT «provide initial or laboratory assessments (*viz.* pre-field) of stove performance in a controlled setting», useful for comparing «the effectiveness of different designs at performing similar tasks» and selecting «the most promising products for field trials» [11]. Such parameters should not be interpreted neither adopted as representative of the real performance which may result on the field when cooking real foods with local fuels. A brief description of the indicators follows:

– *Thermal Efficiency* (η): it is calculated as the ratio of the heat absorbed by water and the heat produced by combustion; the former is computed as the sum of sensible and latent heat, while the latter is computed as fuel burnt times lower heating value of the fuel, both on a dry basis.
– *Emission factors (EF)*: they are calculated for each of the measured pollutants (*viz.* PM and CO) and CO_2. They represent the average mass (expressed in grammes) of pollutants emitted per mass (expresses in kilograms) of fuel burnt. The total mass of each pollutant emitted is obtained by multiplying EFs by the mass of dry fuel burnt.
– *Time to boil* (t_b): it is the time the stove employs to boil a certain quantity of water in the pot required by the WBT (*i.e.* 5 or 2.5 L).

[1] «Cookstoves with [chimneys and] closed combustion chambers were usually considered "improved"». *Household cookstoves, environment, health, and climate change: A new look at an old problem*. World Bank, 2011.

This work aims at assessing energy performances of ICSs in terms of effective saving of fuel use (ε) with respect to three-stone fire stoves (see Appendix A for further details on this definition). To this end, an *Overall Energy Efficiency* – defined as the ratio of the useful heat and the primary fuel energy input (fuel fed into the stove times lower heating value as received) [21,22] – would be an appropriate reference indicator. Conversely, the thermal efficiency η formulation of the WBT is referred to the heat released from combustion, which corresponds to the energy released by only that part of fuel that is actually combusted (referred to as "equivalent dry fuel consumed" [11]). This equivalent amount of fuel burnt is typically lower than the amount of fuel fed into the stove. However, since data obtained from WBT results are usually based on a thermal efficiency η metric, the latter is considered in the present analysis as a reference for the calculation of ε, though the authors recommend to pay attention on its meaning. It is worth noting also that the WBT 4.2.3 itself suggests interpreting this parameter only for the *cs* and *hs* phases of the procedure, as also stated in the ISO-IWA meeting of February 2012 [20]. As a matter of fact, Zhang et al. and Bailis et al. questioned the accuracy and utility of such indicators at *simmering*, respectively in [7] and [23]; indeed, *simmering* phase is characterised by highly variable steam production, which represents a heat loss in the energy balance which conversely contributes positively to the efficiency value in the actual formulation of η, as Jetter et. al. [24] highlighted. Accordingly, in the present analysis we refer only to high power performances.

The saving of fuel use ε indicator can be also obtained from another parameter based on WBT outputs, *i.e.* the *energy use* (e), adopted by N. MacCarty [25]. It is intended as an indicator of the mean thermal energy use of the stove to complete a WBT, and it is calculated as the sum of the amount of dry fuel (kg) burnt during the three phases multiplied by its lower heating value (MJ/kg). As for the calculation of η, also the calculation of e is based on the "equivalent dry fuel consumed" that is typically employed in WBT calculations, rather than the actual fuel fed into the stove.

Data from the literature

We searched for peer-reviewed papers by Science Direct editorial platform and Scopus database, and technical reports within the grey-literature produced by international organizations and institutions, using the following key-words: Improved Cook Stoves, three-stone fire, biomass stoves, developing countries, Water Boiling Test, efficiency. Among all the papers matching our key-words, a selection has been carried out and based on the following rules:

i) stoves must be assessed in the papers through the WBT procedure;
ii) papers and reports must provide a comparison among a reference traditional three-stone fire stove and another supposed "improved" model of cookstove;
iii) the results of energy indicators as thermal efficiency (η) and energy use (e) must be reported with complete statistical information (*viz.* mean and standard deviation (SD) at least);
iv) the fuel used must be wood, in order to perform an equal comparison between ICSs and traditional TSF stoves which are mainly fuelled by wood biomass.

Data used for the evaluation of performance of cookstoves have been collected from the scientific and grey literature: 37 documents among articles and reports have been examined [23,24,26–60], which perform a WBT-comparison among different ICSs and reference traditional TSF stoves. Only 9 papers satisfied the previous four criteria. In Appendix A we provide a summary of information for each selected paper and report: the location (*i.e.* the country) of the study, the tested ICSs – for a comprehensive review of the existing models of ICSs see [38,61,62] – the number of replicates performed and the amount of litres of water used for the tests. We categorized the 9 papers in 3 *Classes*, based on the procedure we employed to evaluate ε in the results of the WBT and the statistical information provided:

Class 1. It concerns only 6 papers for a total of 28 comparisons of ICSs and TSF stoves [23,33,35,53,55,28]. Average and standard deviation of both the cold-start (*cs*) and hot-start (*hs*) thermal efficiency η are given for both the tested ICSs and traditional TSF stoves: therefore we obtain four statistical distributions of η. The ratio quantifying the saving of fuel use ε is:

$$\varepsilon = 1 - \frac{mean(\eta_{TSF,cs}, \eta_{TSF,hs})}{mean(\eta_{ICS,cs}, \eta_{ICS,hs})} \tag{1}$$

In the equation, the thermal efficiency values (η) of ICS and TSF are compared by calculating the average thermal efficiency of the two high power phases (*cs* and *hs*) for both the stoves ($\eta_{TSF,cs}, \eta_{TSF,hs}$ for TSF and $\eta_{ICS,cs}, \eta_{ICS,hs}$ for ICS), as recommended by the WBT 4.2.3 [11].[2]

Class 2. It concerns only 2 papers for a total of 9 comparisons of ICSs and TSF stoves [12,33]. Average and standard deviation of the overall test thermal efficiency – in this case the values of the *cs* and *hs* phases are already averaged – are given: we obtain two distributions of η. The ratio quantifying the saving of fuel use ε is:

$$\varepsilon = 1 - \frac{\eta_{TSF}}{\eta_{ICS}} \tag{2}$$

with η_{TSF} and η_{ICS} the overall test thermal efficiency values of TSF and ICS.

Class 3. It concerns only 1 paper for a total of 20 comparisons of ICSs and TSF stoves [45]. The thermal efficiency is not provided and the indicator directly linked to the performance of the two compared ICSs and TSF stoves is the energy use e: a number of 3–10 tests for each stove results in an interval of feasible values of e and the correspondent algebraic average. The ratio quantifying the saving of fuel use ε is:

$$\varepsilon = 1 - \frac{e_{ICS}}{e_{TSF}} \tag{3}$$

with e_{TSF} and e_{ICS} the overall energy use e values of TSF and ICS.

Appendix B provides further information on the meaning of Eqs. (1)–(3).

Uncertainty analysis performed

In this work, epistemic uncertainty related to η and e of the tests for the three *Classes* arises. Resorting to a single probabilistic representation of epistemic uncertainty may not be possible when sufficient data are not available for statistical analysis [63], since only about 3 tests are available for the same comparison – that is between an ICS and a TSF – under investigation. We therefore adopted possibility distributions (*i.e.* fuzzy sets) to perform an appropriate uncertainty analysis. For *Class 1* and *2*, where the test results are reported by means of the average and standard deviation of η, the approach chosen to construct the possibility distributions related to tests is the Chebyshev inequality (Fig. 2), by which it is possible to describe a probability family containing all distributions with a known mean and standard deviation, whether the unknown probability distribution function is symmetric or not, unimodal or not [9].

[2] Note that some authors question the mathematical appropriateness of averaging these values [7], and alternatives are still under study.

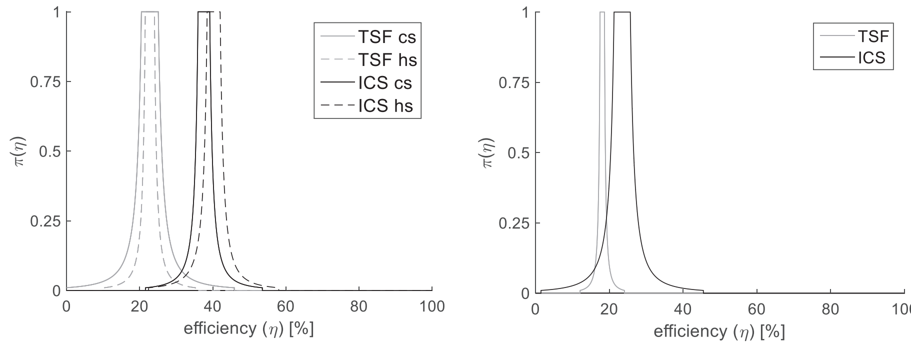

Fig. 2. Chebyshev distributions selected for the input parameters of *Class 1* and *2*.

Instead, *Class 3* needs the adoption of uniform possibility distribution, with the support represented by the interval of results of the tests, given the limited experimental tests performed and the poor statistical information provided (Fig. 3).

Extension principle of fuzzy set theory was applied to propagate uncertainty of input possibility distributions η and e, in order to calculate the resulting possibility distributions of output parameters ε of the models in the three *Classes*. In particular, given the fuzzy sets describing the input quantities, the output parameter distribution π was derived by means of alpha-cuts (α-cuts) evaluation [63]. According to Wierman in [64], «the α-cut of a fuzzy set A is the crisp set comprised of all elements x of universe X for which the membership function of A [the possibility π that x belongs to A] is greater or equal to α»:

$$A_\alpha = \{x \in X | \pi(x) \geqslant \alpha\} \tag{4}$$

According to Baudrit and Dubois [10,65], the extension principle defines the resulting possibility distribution π of parameter ε for all the three *Classes* as following:

$$\pi_\varepsilon(u) = \sup_{y_1, y_1, \ldots, y_n, g(y_1, y_1, \ldots, y_n) = u} \min(\pi_{Y_1}(y_1), \pi_{Y_2}(y_2), \ldots, \pi_{Y_n}(y_n)) \tag{5}$$

where $n = 3$, Y_1, Y_2 …, Y_n represent the input quantities (*viz.* the input parameters coming from the right-hand members of Eqs. (1)–(3) for the three *Classes*) whose uncertainty is described by the fuzzy sets $\pi(y_1), \pi(y_2), \ldots, \pi(y_n)$ (*viz.* the possibility distributions shown in Fig. 2 and Fig. 3 for the three *Classes*), and g expresses the Eqs. (1)–(3) of the three *Classes*.

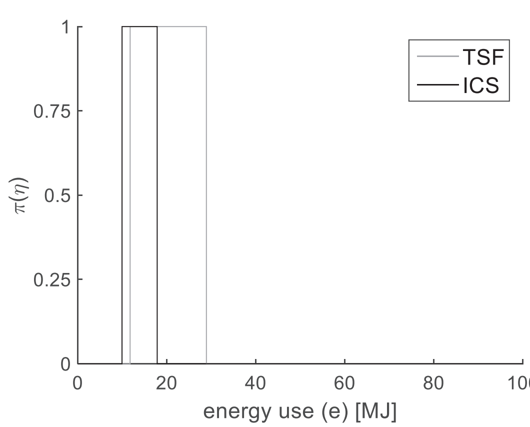

Fig. 3. Distributions selected for the input parameters in *Class 3*.

Results and discussion

We employed the extension principle of fuzzy set theory to obtain the possibility distributions of the output ε for all the comparisons of ICSs and TSF stoves. Fig. 4 reports three possibility distributions, one for each *Class*. The light grey and dark grey lines represent the lower and upper curves of the possibility distributions: given a value of ε in the x-axis, they provide the lower and upper *possibility* that the concerned ICS performs with such value of ε respect to its reference TSF. The dashed line indicates the value of ε for the same stove if only the mean values of the WBT would be considered, without taking into account the epistemic uncertainties of the test results.

Information regarding the percentage of stoves that resulted "improved" under a given degree of confidence was then derived from the global set of stoves' comparisons analysed. In particular, considering the lower curve of ε for every comparison, and counting how many times it exceeds zero for a considered value of α-cut – respectively 0.01, 0.05 and 0.1 in this analysis – it is possible to find the percentage of stoves showing an ε greater than 0 and being considered as improved with respect to the traditional TSF at a 99%, 95% and 90% degree of confidence. Fig. 5 reports the analysis made on the possibility distribution ε of one stove of *Class 1*: for the α-cut equal to 0.05 and 0.1 the value of ε results greater than 0, which means the ICS results as improved with a degree of confidence respectively of 95% and 90%.

Decreasing the degree of confidence (*viz.* increasing the α-cut) allows to find the α-cut in which the percentage of ICSs accounted by propagation of uncertainties equals the percentage resulting from the simple analysis of mean values of WBTs retrieved from the literature (*viz.* the values of ε in correspondence to the dashed lines as in Fig. 4, for each comparison), equal to 75.00%, 100%, 90.00% respectively for *Class 1*, *2* and *3*.

The results reported in Table 1 show that the percentage of the supposed "improved" cook stoves considerably decreases in all the three *Classes* when the uncertainties of the WBT results are considered. Particularly for *Class 2,* the percentage of stoves considered as "improved" at 99% degree of confidence is 0%, with respect to 100% obtained when only the mean values of the WBT are taken into account. However, in all the three *Classes,* at 90% degree of confidence, the percentage of "improved" stoves obtained by considering the mean values of the WBT is 3 times higher than the percentage resulted from this analysis at least. Moreover, for *Class 1* and *3*, the percentage of "improved" stoves obtained from the simple analysis of the WBT's results, respectively equal to 75.00% and 90.00%, is reached in our analysis only by considering the core of the possibility distributions of ε where the α-cut is 1. It means that no relevant conclusions can be drawn for the probability of occurrence since it is comprised between 0 and 1, giving no useful

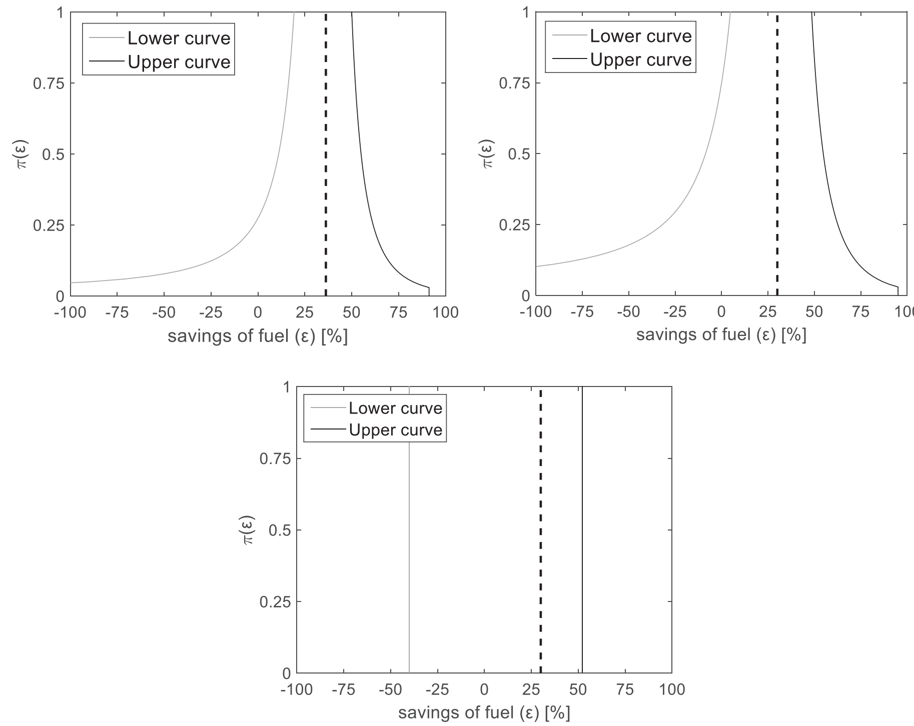

Fig. 4. Representation of ε for three stoves of *Class 1* (top-left), *Class 2* (top-right) and *Class 3* (bottom-centre) evaluated through the fuzzy set theory.

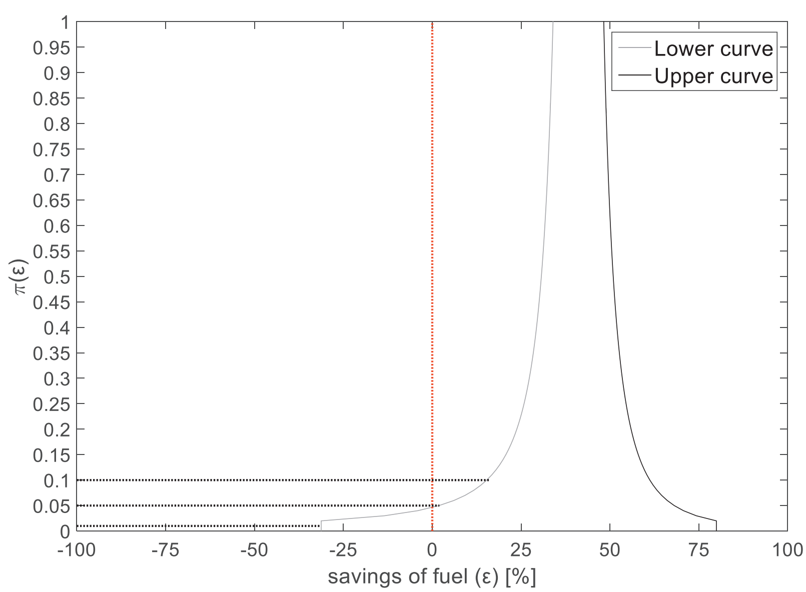

Fig. 5. Evaluation of the real improvement of a stove for different α-cut (0.01, 0.05, 0.10).

information. Instead, analysing the *Class 2*, 100% of ICSs is found in correspondence to the α-cut equal to 0.33: the degree of confidence results higher than the other two *Classes*, meaning that we can infer that all the stoves are "improved" at 67% confidence level – we accept an error of 33% with this inference.

The previous results refer to the general category of ICSs. To conduct a more in-depth analysis, we created clusters of ICSs for all the three *Classes* based on their shape and material, in order to pool the results by the *averaging* method [66], which consists in averaging the limiting upper and lower distributions of ε of each ICS belonging to the same cluster. Table 4 in Appendix C reports the description of the main characteristics of each cluster of ICSs: *Mud stove*, *Clay stove*, *Metal stove*, *Rocket stove*, *Micro-Gasifier*, *Stove with FAN*, *2 pot-stove*. Table 2 reports the interval of possibility through that the stoves can be considered as "improved" – with ε greater than 0 – within the different clusters. In *Class 1*, when the results of the WBTs analysed report all the relevant statistical information, the unique model of stoves that could be considered as improved with higher confidence degree is the *Stove with fan*. Indeed, this model has a fan, which provides air flow into the combustion chamber, powered by an external source of electricity or by a direct-coupled thermoelectric generator (TEG) module that blows high velocity, low volume jets of air into the combustion chamber, resulting in a more complete combustion of the fuel. In

Table 1
Percentage of stoves considered as improved (ε > 0) at different degrees of confidence.

	α-cut	Degree of confidence (%)	Percentage of "improved" stoves
Class 1	0.01	99	3.57
	0.05	95	10.71
	0.1	90	17.86
	1	0	**75.00**
Class 2	0.01	99	0.00
	0.05	95	11.11
	0.1	90	22.22
	0.33	67	**100.00**
Class 3	0.01	99	15.00
	0.05	95	15.00
	0.1	90	15.00
	1	0	**90.00**

Class 2, which refers only to 2 papers found from the literature, the possibility to consider *Mud stove* and *Clay stove* as "improved" is always larger than 74%. In *Class 3*, no relevant conclusions can be drawn about the possibility to consider the stoves as "improved", since the lower limiting probability value is always lower than 0.33. This is mainly due to the poor statistical information provided by the paper of this *Class*, which allowed the authors to adopt only a uniform possibility distribution to represent the input parameters.

In the end, the results obtained in this work seem to suggest the possible advantage of employing possibility theory to deduce the statistical inferences from very small sample sizes – such as the typical three test replicates. As a matter of fact, when dealing with a very limited number of test replicates, the calculation of the related variance may bias *t*-test-based or *normality test*-based statistical inferences. Wang et al. [8] propose addressing this issue by relying on a default value of variance (derived from their study), rather than estimating it based on three test replicates. By using this value and assuming a t-distribution, they propose calculating *a priori* a "minimum number of replicates" needed to achieve a certain level of confidence, which should be subsequently corrected considering a 100% margin of safety. Nevertheless, the high margin of safety needed to compensate for the uncertainty about the applicability of the default value of variance to a different test series may still lead to a very large "minimum number of replicates", which may be rejected by testers for time reasons. In this case, possibility theory may provide a consistent method to perform the statistical analysis of test results when imprecise knowledge and epistemic uncertainty related to small samples arise. Indeed, possibility theory would allow to achieve more conservative conclusions based on such preliminary few test results, which may be strengthened by t-student approach once more data are collected. Nevertheless, further studies would be needed to clearly define a threshold number of replicates below or above which it may be preferable to use the proposed possibility theory or the traditional t-student approach, respectively. Wang et al. [8] indicate that, «as a rule-of-thumb» based on their experience, the t-student approach should not be used with less than five replicates. However, this threshold number may increase to seven, eight or more replicates in case of different testing conditions (e.g. less trained testers).

Conclusion

This work proposes a study based on possibility theory to critically analyse data retrieved from the literature regarding WBTs on ICSs and traditional TSF stoves. Data are affected by incomplete knowledge and epistemic uncertainty. We categorized them in three *Classes* based on the statistical information provided: for two *Classes*, we were able to represent the uncertainty through a Chebyshev distribution, while we adopted a uniform distribution for the last one. We applied the extension principle of fuzzy set theory to evaluate, at 99, 95 and 90% degree of confidence, the percentage of stoves that reveal an effective improvement in terms of fuel savings (ε) with respect to traditional TSF stoves; we clustered them, evaluating the possibility to consider them as "improved" within the same group.

The results suggest how considering only the mean values of the outputs of the WBT and neglecting intrinsic uncertainties of the results may lead to make large errors and misinterpretations regarding the ICSs' performance. Indeed, for all the three *Classes* analysed, at 90% degree of confidence, the percentage of "improved" stoves obtained by considering the mean values of the WBT is among 3 and 6 times higher than the percentage resulted from this analysis at least. At 99% confidence level, only 15% of all the supposed "improved" stoves emerged as real ICSs at most. When enough statistical information is provided from WBT results, only the *Stove with fan* model of cookstoves seemed to reveal real improvements with a probability greater than 93%.

This work shows how neglecting the epistemic statistical uncertainties originated from WBTs – as done by a large portion of the literature, which reports results from few lab-tests replicates without sufficient statistical information – might lead to misinterpreted evaluations of ICSs' performance, with potential negative impact on beneficiaries. Such conclusion may lead to a more accurate approach to conduct ICSs testing campaigns and to report the results in a more comprehensive way, by paying greater attention to statistical issues and to the statistical method adopted to process the results. In the end, the authors wish this research will encourage a more in-depth research on the issue of performance evaluation of ICSs at the international level, since the WBT-based literature does not seem to completely prove, at acceptable degrees of confidence and apart from the *Stove with fan* model, the effective improvements of ICSs, in terms of fuel depletion, with respect to traditional and considered "inefficient" TSF stoves.

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Appendix A

See Table 3.

Table 2
Possibility that the analysed stoves have $\varepsilon > 0$ for the different clusters.

	Mud stove	Clay stove	Metal stove	Rocket stove	Micro-Gasifier	Stove with FAN	2 pot-stove
Class 1	–	$0.14 \leqslant P \leqslant 1$	$0.60 \leqslant P \leqslant 1$	$0.39 \leqslant P \leqslant 1$	–	$0.93 \leqslant P \leqslant 1$	$0.15 \leqslant P \leqslant 0.94$
Class 2	$0.74 \leqslant P \leqslant 1$	$0.96 \leqslant P \leqslant 1$	$0.58 \leqslant P \leqslant 1$	–	–	–	$0.65 \leqslant P \leqslant 1$
Class 3	$0 \leqslant P \leqslant 1$	$0 \leqslant P \leqslant 1$	$0 \leqslant P \leqslant 1$	$0.11 \leqslant P \leqslant 1$	$0 \leqslant P \leqslant 1$	$0.33 \leqslant P \leqslant 1$	–

Table 3
Overview of papers and reports selected for the analysis.

N.	Reference	Location	Categories of tested ICSs	N. replicates performed	Litres used for the test
1	[23]	India	2-pot stoves Clay stoves	3	3[a]
2	[33]	Sustainable Energy Development Centre (SEDC)	2-pot stoves	3 for TSF 4 for ICS	Not specified
3	[35]	U.S. EPA, United States	Metal stoves Rocket stoves Stoves with FAN	3	5
4	[53]	Aprovecho Research Center, USA	Metal stoves Clay stove 2-pot stoves Stoves with FAN Rocket stoves	3	5
5	[55]	University of Agriculture, Makurdi, Nigeria	Clay stove	3	5
6	[28]	GIRA's laboratory, Patzcuaro Michoacan, Mexico	2-pot stoves	3	3
7	[27]	Johannesburg, South Africa	Metal stove 2-pot stoves	6 for TSF and one ICS 5 for one ICS	2
8	[48]	OGI School of Science and Engineering, Oregon, USA	Metal stove Clay stove	3	Not specified
9	[45]	Aprovecho Research Center, USA	Clay stove Mud stove Metal stove Rocket stove Micro-Gasifier Stove with FAN	3 "or more"	5 L (2.5 L for small stoves)

[a] It is assumed they adopted the same methodology employed in [28], since they reported that «comprehensive analysis of the results of the stove-testing conducted by GIRA may be found in (Berrueta et al., 2007)».

Appendix B

We demonstrate here the meaning and the origin of Eqs. (1)–(3). The approach is the same for both the first two equations that refer to the thermal efficiency indicator η. We show the demonstration only for the Eq. (2) for clarity. The secondary energy between an ICS (E_{II}^{ICS}) and a TSF (E_{II}^{ICS}) being equal (*viz.* the secondary energy needed for bringing the water to the boil in the WBT, and the secondary energy required by food to be cooked in real field use), the energy balance states that:

$$E_{II}^{ICS} = E_{II}^{TSF} \tag{6}$$

Knowing the WBT-based thermal efficiency η of the stoves, it is possible to express E_{II} as a function of the primary energy delivered to the stoves by the fuel:

$$\eta_{ICS}E_{I}^{ICS} = \eta_{TSF}E_{I}^{TSF} \tag{7}$$

that is

$$\eta_{ICS}m_{wood}^{ICS}LHV = \eta_{TSF}m_{wood}^{TSF}LHV \tag{8}$$

with m the mass and LHV the lower heating value of the fuel burnt in the stove. Since the stoves are tested with the same fuel, simplifying and arranging the equation we obtain:

$$\frac{m_{wood}^{TSF} - m_{wood}^{ICS}}{m_{wood}^{TSF}} = 1 - \frac{\eta_{TSF}}{\eta_{ICS}} \tag{9}$$

The left term represents the saving of fuel use ε of Eq. (2). Eq. (1) differs only in the fact that the thermal efficiency of both the ICS and the TSF stove is expressed as the average among the cold and hot start phases of the WBT.

The approach for demonstrating the origin of Eq. (3) starts with the expression of the parameter saving of fuel use ε:

$$\varepsilon = \frac{m_{wood}^{TSF} - m_{wood}^{ICS}}{m_{wood}^{TSF}} \tag{10}$$

By multiplying each mass term by the corresponding lower heating value LHV, we obtain the definition of *energy use* (e), so that the Eq. (10) takes the form of Eq. (3):

$$\varepsilon = \frac{m_{wood}^{TSF}LHV - m_{wood}^{ICS}LHV}{m_{wood}^{TSF}LHV} = \frac{e^{TSF} - e^{ICS}}{e^{TSF}} = 1 - \frac{e^{ICS}}{e^{TSF}} \tag{11}$$

Appendix C

Table 4
Description of the identified Clusters of ICSs.

Cluster	Description
Mud stove	Mud stoves are structures commonly made of sun-dried mud or mud dried by heat from the fire, with a hole for placing the pot on the top and three sides that enclose the fire. They are semi-permanent stoves and usually directly built-on-site. According to Milind P. Kshirsagar [38], examples of traditional models include chullah, angithi, and haroo in India [67] and Mogogo models in Africa
Clay stove	Within the category "clay stoves", we include also the Ceramic stoves, and all the devices that are made of sand, clay, straw, mica, sawdust and grass, mixed with binding materials, as mud stoves. The major difference is the possibility of baking the raw material in an appropriate kiln that increases the durability and reliability of the material. Traditional models promoted by international programmes are the Upesi (also known as Maendeleo) stove in Kenya [61,68] and the Chitetezo Mbaula in Malawi [61,68,69]
Uninsulated Metal stove	Metal stoves are the cookstoves made of steel, sheet metal, or cast iron. They are not insulated and can easily be built using scrap metal such as cooking oil containers or old oil drums. Milind P. Kshirsagar reports some examples of traditional models [38]: Jumla stove in Nepal and Bukhari, MA-II and I in South-Asian regions [70]. More recent and commercial models exist as well, like Vikram, Harsha and Magh stove in India [71,72]
Rocket stove	With the term Rocket stove we refer to a designed model of stoves with a combustion chamber made up of two orthogonal parts: an insulated upright chimney (with a height of two or three times the diameter) and a horizontal zone where wood sticks are placed. Different models exist, from domestic to institutional use, insulated or not, with and without skirt. The Rocket design is the most widespread model among commercial ICSs, like the Envirofit International's Family of Rocket stoves [38]
Micro-Gasifier	The term micro-gasifier or wood-gas stove means a model of stove which works via two-stages combustion: the biomass fuel is first burnt in the lower part of the combustion chamber, causing a decomposition of the biomass into volatile gases and vapours, pyrolysing fuel and producing a solid char that could remain behind or consequently be burnt up. Through a second flux of air towards the top of the stove, the gases that are released in the first stage are mixed and burnt (Gas-combustion) [73]. Examples are the Oorja and Philips stoves [74,75]

Table 4 (*continued*)

Cluster	Description
Stove with FAN	This category includes all the stoves that have a blower injecting air above the fire, which aims at improving the combustion efficiency. The blower is usually powered by external source of electricity or coupled with a thermoelectric generator (TEG) directly in the stove chamber, which can produce small amounts of electricity exploiting the Seebeck effect
2 pot-stove	This wide category of stoves includes all the existing models of wood cookstoves that are designed for arranging 2 pots at least, which may be sunken or not. Distinctions based on the material were not considered. Examples of traditional models are Plancha in Central and South America [28], and Okoa in Tanzania [33]

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