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LABORATORY ESTIMATION OF ELEMENTAL AND ORGANIC CARBON EMISSIONS FROM ADVANCED BIOMASS STOVES IN SENEGAL

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A B S T R A C T

In this study, we tested a natural draft gasifier, currently implemented in Senegal and the traditional three stones fire (TSF) in the laboratory, using the protocol of water boiling test (WBT). Pollutants emissions from three types of biomass full were investigated in this work. Our results show that, burning the same wood (*Cordyla Pinnata*, dimb), the gasifier had a fuel consumption 37% lower than the traditional three stones, and decrease emissions factors of fine particulate matter (PM) by 74%, organic carbon (OC) by 59 % and elemental carbon (EC) by 55%. The gasifier has also shown to reduce fuel used and emissions compared with the three stones using *Casuarina Equisetifolia (Filao)* though to a minor extent: 24 % in fuel consumption and emissions reduction of 53% of PM, 55% of OC and 18% EC. The micro-gasifier using typha pellets is the cooking system the most efficient with a reduction 70% of fuel and more than 85% of emissions comparing to the 3-stones-dimb combination.

Our results agree with other studies and confirm that gasifier have a very low fuel consumption and low emissions of climate forcing particles. Further field studies are needed to evaluate the adoption of these new stoves and fuels and to analyze fuel consumption and emissions under real-world cooking practices.

I. INTRODUCTION

In sub-Saharan Africa (SSA), four out of five people resort to the traditional use of solid biomass, mainly firewood, for cooking [IEA, 2016; Africa Energy Outlook, 2014]. As a consequence, some of the earth's natural forests are being depleted, which in turn, contributes to climate change. Many women and children are forced to spend long hours every day collecting cooking fuel.

The most common cooking technologies used are traditional biomass stoves, which emit a significant amount of gases (carbon dioxide, methane, hydrocarbons, carbon monoxide and oxides of nitrogen) and particulate matter (PM), which are a threat to health and have strong effects on the climate [Bond., 2004; Venkataraman et al., 2005; Chafe et al., 2014]. In sub-Saharan Africa, indoor air pollution (IAP) exposure is the single greatest health risk for women and girls [WHO, 2016; WHO (Ed.), 2014], causing around half a million premature deaths annually, half of them of children under five. If no action is taken, by 2030, 870,000 people will die annually from diseases linked to solid fuel cooking. Elemental Carbon (EC) is a part of particulate matter, it is a short-lived climate pollutant and the second largest contributor to global warming [Jacobson et al., 2001]. It is estimated that the residential solid fuel burning accounts for 25% of global elemental carbon emissions [GACC, 2013]. EC is always emitted with co-pollutant particles, such as organic carbon and sulphates, which can have a neutral or even cooling effect on the climate [Chung et al., 2002]. The ratio of EC to its co-pollutants varies depending on the emission source and fuel-type, and impacts whether the source has a net-positive or -negative warming effect [EPA, 2014]. Several health studies have found that elemental carbon is associated with a risk 7-10 times higher per microgram per cubic meter than $PM_{2.5}$ [WHO, 2012].

It is in this light that many countries in the Sahel region adopted a "Domestic Energy Strategy", focused on the reliable management of forest resources and the promotion of improved cooking solutions, primarily based on the rocket stove technologies [CILLS, 2008].

According to some laboratory studies, the rocket-type stoves can reduce fuel use CO and $PM_{2.5}$ emissions in comparison to the three-stone fire [Nordica et al., 2010]. But, in spite of these benefits, they are still far from clean combustion, defined by the WHO Guidelines for indoor air quality: household fuel combustion and the ISO IWA 11:2012 Guidelines [ISO, 2012]. Moreover, some rocket stoves types showed higher EC emissions when compared to the traditional stoves [Bond, 2004; Cachier et al., 2096; de la Sota et al., 2020; MacCarty et al., 2008a; Rau, 2089].

Therefore, technologies and fuels with higher emissions reductions are needed to substantially reduce health and climate risk [Smith, 2010], together with the promotion of adequate ventilation practices (chimneys, kitchen materials, windows, etc.) and ensuring a correct and sustained used of the technologies.

Thereby, the gasifiers offer the opportunity of provide significant emission reductions [Jetter et al., 2009; MacCarty, 2008b; Roth, 2011]. Most of the micro-gasifier cookstoves use the top-lit up draft (TLUD) design [Anderson et al., 2007], which allows for air-control and respect the three T's of clean combustion (time, temperature and turbulence).

Recent cookstove testing by the U.S. Environmental Protection Agency (US-EPA) has provided evidence that gasifier cookstoves are currently the cleanest and most efficient options for utilizing solid biomass fuels for cooking. They can reduce particulate matter substantially, averaging 90% improvement over the three-stone fire [MacCarty et al., 2010; Jetter et al., 2009]. But the performance and emission during fuel combustion depend on many factors, including flame temperature, composition and concentration of combustion reactants, and residence time within the reaction zone [Shurupov, 2000; Christian et al., 2012]. Thus, each of these factors can vary according to the specific design of the stove and type of fuel used.

Despite the ongoing efforts to increase the capacity for testing, a lot of advanced biomass technologies used in sub-Saharan Africa have not been already tested and there is no quantitative data regarding the emission reductions achieved the fuel efficiency, etc. The data scarcity are especially high regarding elemental (black) carbon, organic carbon, and other short lived climate pollutants.

In this study, the thermal efficiency and emissions of the traditional stove (3-stone fire), widely used in sub-Saharan Africa, were compared with those of the Prime Square Cookstove which is a natural-draft gasifier, with a TLUD design. The study was conducted under laboratory conditions at the Centre d'Etudes et de Recherches sur les Energies Renouvelables (CERER), -. In Senegal, the *Social and Ecological Management Fund (SEM-FUND)* program aims to replace 30.000 inefficient stoves with this stove model in households in urban and peri-urban areas throughout the country, with funding from the World Bank [SEM-FUND]. These cooking technologies were tested when burning three types of wood fuel species: Casuarina Equisetifolia (Filao), Cordyla Pinnata (Dimb) and Typha domingensis *(* typha pellets).

II. MATERIALS AND METHODS

2.1 Stoves tested

Prime Square Stove: The stove is made in Indonesia and produced by Prime Cookstoves (fig.1). The Prime Square Biomass Cookstove design is based on a kerosene stove design commonly used in Indonesia. It has a primary and a secondary air regulator, in addition to a large stove table and four legs for stability. The stove doesn't have a fan, and the flame intensity can be controlled with a rotary knobs. The combustion chamber is made of heat-resistant parts and its maximum capacity is about 1.5 kg of biomass pellets, which can give a flame up to 2 hours. [Prime Indonesia]

Fig.1. Prime Square Stove

The legs are commonly also used as handles to move the stove or to empty it for ash or biochar after cooking. The main fuel for the stove are biomass pellets (cylinder shaped with diameter 6-8mm), but the stove also can use agricultural and plantation waste, such as coarse palm kernel shells candlenut shells, peanut shells, or even small pieces of wood. The stove can be used with all types of aluminum pots with a minimum diameter of 12 cm and maximum 40 cm. These characteristics demonstrate the versatility of the stove.

Three Stones or Traditional stove: The traditional three stones or open fire still remains the most common method of cooking in rural areas in Senegal, and the majority of rural areas of sub-Saharan Africa,

2.2 Fuels tested

Cordyla Pinnata belongs to the family of leguminosae. It may be found in dry forest and wooded savannah zones from Senegal east to Niger, northern Nigeria and northern Cameroon. In savanna parklands in Senegal, it is the dominant woody specie. The tree reaches a height of 13 to 20 m, with short boles. It is a true multipurpose tree, not only yielding wood but also edible fruits and traditional medicines. Cordyla pinnata has been suggested for planting in the Sahel and Sahelo-Soudanian regions for reforestation. The common name in Senegal is Dimb [PROTA].

Casuarina Equisetifolia : It is a she-oak specie of the genus *Casuarina*. The native range extends from Burma and Vietnam throughout east Malaysia to French Polynesia, New Caledonia, Vanuatu, and south to Australia *Casuarina equisetifolia* is an evergreen tree growing to 6–35 m in height. The foliage consists of slender, much-branched green to grey-green twigs 0.5–1 mm diameter. The common name in Senegal is Filao [Wikipedia].

Typha pellets: Salvinia Typha (or Typha Australis) is an invasive aquatic plant in Senegal that prevents livestock from drinking and fishermen from working properly. All this contributes to the degradation of the water quality of the river and to the blockage of the soil and draining systems [Amadou et al., 2009; Caro et al., 2011]. The Typha Australis grows aggressively and covers large parts of the Senegal River, leading to many problems, such as blocking irrigation canals, making access to the river and fishing difficult for the local population, attracting bird pests that invade rice plots and increasing health problems that result from stagnant water [Amadou et al., 2009].

At the same time, Senegal is facing a considerable deforestation problem, characterized by a decreasing vegetation cover, soil erosion and diminished fertility, in a country where more of 50% of the total population depends on the agricultural sector [ANSD]. The use of wood and charcoal contributes to desertification in the country and southern expansion of the Sahel region [Amadou et al., 2009].

In order to encourage the removal of Typha, Senegalese public officials and academics have considered the promotion of Typha as commercial biomass material, contributing at the same time to decrease the pressure on the forests. One of these options is its use as a feedstock for fuel pellets [Caro et al., 2011].

The proximate analysis of the fuels used is given in table 1. Measured moisture content and calorific values for the fuels are used to calculate the emission factors and the specific fuel consumption.

Table 1: Fuel characteristics

Fuel	Moisture content (%)	calorific value (MJ KG^{-1})	Ash (%)	Volatile matter (%)	Fixed carbon (%)
Dimb (cordyla pinnata)	8,80	21,31	3,02	77,5	0,49
Filao (casuarina equisetifolia)	7,92	20,00	0,48	86,22	5,38
Typha Pellet	3,00	20,31	10,88	75,24	3,65

2.3 Test system

The Laboratory Emission Monitoring System, (LEMS), developed by Aprovecho Research Center was used for laboratory emissions collection and measurement [ARC]. The LEMS consists of a hood structure, a blower, a flow measurement system and a sampling emissions system. The LEMS measures the total emissions produced during stove combustion. The stove is placed under a hood which collects the emissions and air from the laboratory. The flow rate and exhaust temperature are measured in the exhaust tube. A fraction of the flow through the system is drawn by a suction pump through a sample line to the sensors. Separately, a thermocouple measurement logs the (water) pot temperature. A computer displays and records the temperatures, flow and concentrations in real-time *(Figure 2).*

The tester then processes the recorded data (.csv file) using a software to report the performance of the stove based on the mass of emissions measured. The gravimetric system gives a direct measurement of total PM using filter-based sampling. A vacuum pump pulls a sample through the sample line and the critical orifice, which holds the flow at a steady 16.7 L/min. A cyclone particle separator is used so that all $PM_{2.5}$ is collected on a filter while the pump is on [Aprovecho Research Center, 2013].

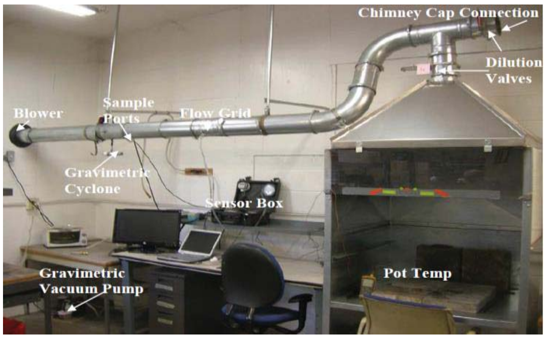

Fig 2: LEMS hood,Ducting, and Gravimetric Assembly.[ARC]

A modification of the gravimetric system was designed by the ARC to carry out the analysis of EC. The EC part adds at the LEMS system a second sample train that runs in parallel with the gravimetric sample train. The EC sample train shares the sample pump of the gravimetric sample train. A separate critical orifice with a lower flow rating (3 LPM) is used as well as a separate filter holder, sample port, and cyclonic particle separator. Having a separate EC sample train allows for $PM_{2.5}$ and EC samples of different masses to be collected simultaneously, and for different types of filter media to be used.

2.4 Testing Procedure

For the collection samples, we used the protocol of Water Boiling Test (WBT). To test the gasifier, we used a modified of the "high power burn-out" version of WBT 4.2.3 (WBT 4.2.3), defined in the framework of comparative tests organized by the Global Alliancefor Clean Cookstoves (GACC) between 22 Regional Testing and Knowledge Centres (RTKC) in the world, in 2014. During the test, a certain amount of water is brought to boil and kept simmering just below the rolling boil until the temperature decreases least 5 degrees with regard to the boiling temperature. For the 3 stones, we used the the WBT version 4.3.2 with two phases: cold start and simmer phase of 45 minutes of duration.

Filter-based technique used to determine EC content.

The particles collected on quartz membrane filters of 10 cm diameter during the tests by the gravimetric system were analyzed using a thermo-optical based technique. The Sunset Laboratory Dual Optics Carbon Analyzer determines the elemental carbon (EC) and OC content by using a thermal optical method (*EUSAAR Protocol 2*) [Cavalli et al., 2010] based on transmission. Hereafter this method will be referred to as TOT (thermo-optical transmittance).

III. RESULTS AND DISCUSSION

Time to boil, thermal efficiency and specific fuel consumption to complete the WBT are represented in Table 2. These parameters were used as the basis to compare the energy efficiency of the stove-fuel combination tested. For comparison of emissions, emission factors of $PM_{2.5}$ (EF $PM_{2.5}$), OC (EF OC) and EC (EF EC) were used. These EFs are represented by the figures 3, 4 and 5.

3.1 Stoves performance

Results on table 2 show that the gasifier reduces the time to boil and the fuel consumption when compared to the three stones. Morevover, this reduction depends on the type of fuel used. The time to boil of the gasifier when burning dimb and filao fuels were the same, 20 minutes, while for the 3 stones it was 35 minutes with the dimb and 30 minutes with the filao. Therefore, saving time was equal to 16 minutes with dimb and 11 minutes with filao. The gasifier showed also a higher thermal efficiency than the three stones, and it was also dependent on the type of fuel used. Gasifier had a thermal efficiency of 26.87% with dimb and 25.57% with filao, while the 3 stones fire had 22.60% with dimb and 20.14% with filao. The same thing happens for the specific consumption, with a 50.90% reduction of fuel with dimb and 58.84 with filao thanks to the use of the gasifier in comparison with the traditional stove

When gasifier burned typha pellets, time to boil was 24±8 minutes, higher than burning dimb and filao (20±2 and 20±3 minutes, respectively) similar to values found by Nordica [MacCarty et al., 2010]; whereas however, the thermal efficiency was much higher with pellets than with the small pieces of wood dimb and filao: 53,90±1,96% with the thypa pellets, in comparison with 26,87±1,18% with dimb and 25,57±1,60% with filao. Moreover, typha pellets conducted to a lower specific fuel consumption (108,85±4,80 g l^{-1}), in comparison with dimb (176,28±11,25 g l^{-1}) and filao (168,90±7,21 g l^{-1})

This proves that pellets are more suitable fuel for cooking with the gasifier than small pieces of wood. Compared to the energy performance results found in the literature, the time to boil and the specific consumption obtained are much higher for both stoves [37; 36] as well as their thermal efficiency is lower than those found in the literature [Jetter et al., 2006; Raman et al., 2013; Carter et al.,2014].

Table 2: Stoves performance

Stove	Fuel	Time to boil (minutes)	Thermal efficiency (%)	Specific fuel consumption (g l^{-1})
3 stones	Dimb	35±1	22,6±2.9	266,01±8.59
	Filao	30±4	20,14±3.04	368,28±7.34
Gasifier	Dimb	20±2	26,87±1,18	176,28±11,25
	Filao	20±3	25,57±1,60	168,90±7,21
	Pellet	24±8	53,90±1,96	108,85±4,80

3.2 Emission factors of PM2.5, EC and OC (g/MJ)

To determine the real impact of the type of stove and fuel on total EC, OC and PM emissions, it is necessary to take into account the fuel consumed by each cooking system. Figures 3, 4 and 5 present PM, EC and OC emissions factors, respectively, to complete a standardized WBT with 5 liters of water and two phases: cold start and simmer phase (of 45 minutes of duration).

The type of stove shows a significant effect on the EF, which is related to the nature of combustion *(combustion occurred in the gasifier explained in previous section*). The three-stone fire produces a larger bed of charcoal under the flaming fuel and the gasifier stove creates little flame but more charcoal [MacCarty et al., 2008b]. , producing lower emissions than the traditional stove for all the pollutant tested.

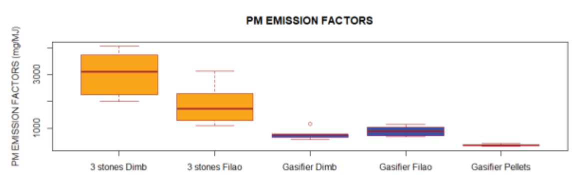

Fig 3: Emission factors of PM (mg/MJ)

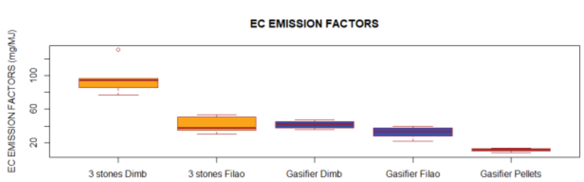

Fig 4: Emission factors of EC (mg/MJ-)

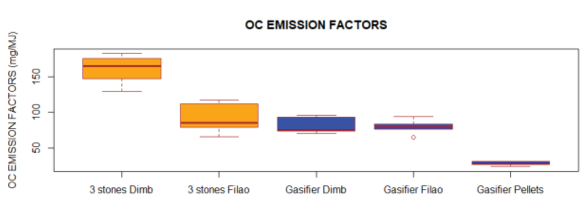

Fig 5: Emission factors of OC (mg/MJ)

EFs value of PM, OC and EC using dimb with the 3 stones fire were respectively 3038,33 mg PM MJ^{-1}, 209,67 mg OC MJ^{-1} and 91, 09 mg MJ^{-1} and 777,18 mg PM MJ^{-1}, 81,38 mg OC MJ^{-1}, 41, 02 mg MJ^{-1} with the gasifier. This means a reduction of 74% for PM, 59% for OC and 55% for EC. Burning filao was found to generate 53% of PM, 55% of OC and 18% EC higher emissions with the traditional stove than with the gasifier. However, they are all more important than the emissions obtained with the philips in the laboratory [Arora et al., 2015; Jetter et al., 2009]

Regarding the fuel effect on emissions, the EF from burning dimb was higher than using filao in both stoves. This confirms that wood species are important factor influencing emissions, sometimes even higher than the type of stove used. Indeed, the gasifier using dimb has higher emission factor than the three stones using filao.

However, not all the types of stoves are influenced by this emissions factor in the same order of magnitude and it is necessary to compare our results with other results found in other studies conducted in similar conditions

The typha pellets were only used in the gasifier, showing the lowest emission factors of all the cooking systems (combination of fuel and stove) tested with value of EC and OC similar emission factor found by Guofeng Shen [Shen et al., 2012] with corn straw pellet as fuel Compared with the 3 stones-dimb (the stove-fuel combination with the highest emissions), the gasifier with typha pellets had EFs lower of 88% for the PM, 86% for OC and 88% for EC.

3.3 Effect of fuel type on emission factors by stove

Figure 6 shows the impact of the wood species with a cookstove on the production of different types of pollutants. And that the use of Dimb wood leads to a significant production of PM, EC and OC emissions compared to the use of filao wood as fuel with the 3-stones fire. While with the gasifier, we have a slight variation of the EC and OC emissions produced by both types of wood while the emissions of PM are much higher with the filao wood.

For pellets that are only used with gasifier because of their size, the results obtained show a significant reduction in emissions of more than 50% compared to those obtained with wood. This variation in emissions by fuel type has been found in previous studies [Jessica et al., 2014].

Overall, our results agree with previous experimental works [Roden et al., 2006; Carter et al., 2014; Shen et al., 2012], confirming that the gasifier (and the pellets) is a biomass cookstove with very low emissions of climate forcing particles.

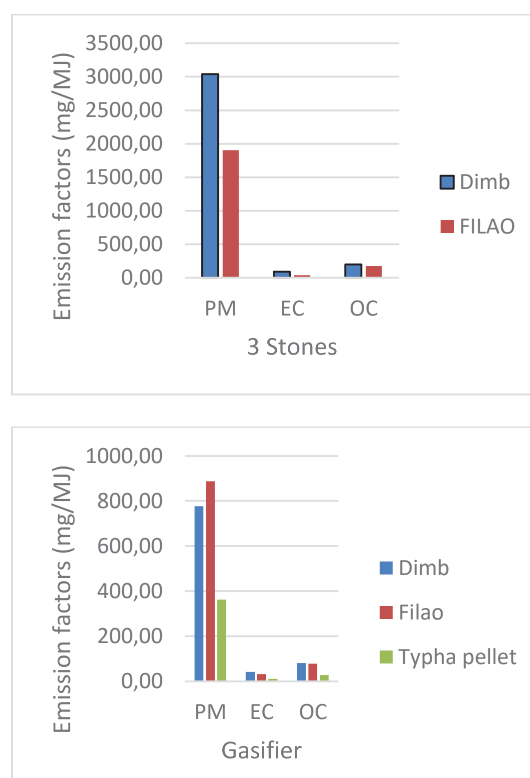

Figure 6: Emission factors by type of fuel for each stove

IV. CONCLUSIONS

This study is the first one done with gasifiers burning the specific types of wood used in Senegal, so the data provided is very relevant.

However, lot of studies have shown that laboratory tests are very different from field studies, and, while laboratory results may be useful to intercompare cooking systems under standardized conditions, field studies need to be conducted to quantify emissions taking into account actual cooking practices.

Results of our tests agree with other studies and confirm that gasifiers are a type of biomass cookstoves with very low fuel consumption and low emissions of climate forcing particles. Thus, they can be a suitable solution for many places where biomass fuel is expected to be the main fuel resource in the next 30 years, as Senegal and many other African countries [IEA, 2016]. However, a sustainable adoption of micro-gasifiers to replace the traditional stoves faces some important challenges.

For example, gasifiers may fail to cover the household's preferences and needs as they are often top-loading only, meaning that the fuel must be fed into the chamber from above; they require much more frequent re-loading of fuel during cooking sessions; fan gasifiers may need electricity, which is not available in many regions; and fuelwood pieces need to be quite small, adding extra work to the cooking-related activities. Moreover, gasifiers are usually significantly more expensive when compared to other basic biomass improved stoves.

Hardware alone is not enough when disseminating a new technology and the skills needed to operate the hardware properly are crucial [Roth, 2011]. Also, there are factors like the operation convenience and cost of fuel and the stove; public knowledge and awareness of environmental and health protection and energy saving; location, household setting and structure, family size, age and gender; the financial support and market development and the existence of favorable policies including laws, regulations and standards [Shen et al., 2012].

The use of typha pellets has shown the lowest EF and fuel consumption compared with other two types of wood species widely used in Senegal (cordyla pinnata and casuarina equisetifolia). Typha is an invasive water plant which is a major environmental challenge in the region, but which presents also the opportunity to be used as feedstock for fuel pellets in Senegal, helping to change a national problem into durable wealth.

Overall, the program of dissemination of 30,000 gasifiers in Senegal by SEM FUND could bring great benefits with regard to human health and climate. We strongly recommend implementing field studies to evaluate the adoption of these new stoves and fuels and to analyze fuel consumption and emissions under real-world cooking practices.

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