CHAR:ME: biochar and biomass-derived waste products as sustainable and safe domestic fuel.

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Abstract
Sub-Saharan Africa suffers from extensive forest exploitation, posing large threats to biodiversity and forest cover. The main driving forces are coal production and domestic cooking practices, which have a significant impact on both the environment and human health conditions. To tackle these challenges, the CHAR:ME initiative arises, focusing on repurposing organic wastes into solid fuels (biochar) as alternatives to wood and wood charcoal. Focusing on the Madagascar region of Antsiranana, the project revolves around the development of a new kind of biomass pyrolytic stove to substitute the obsolete technology, currently widely diffuse in these regions. This innovative stove uses biomass briquettes derived from local waste through mechanical compression and bio-drying techniques as feedstock. The gathering of experimental measurements to characterize the available biomass sources was carried out also considering the endangered species involved. Subsequently, the use of advanced scientific methodologies, such as semi-detailed kinetic mechanisms, and 0D and 1D models, were used to determine heating value and yields from the selected feedstock. Then, these models were coupled with full-scale reactor CFD simulation to drive and refine its design. Overall, the project streamlines the entire process from biomass waste generation to reactor operation, advocating for waste recovery and transformation to mitigate adverse environmental and social repercussions. Ultimately, this technology is planned for dissemination on a community scale, addressing the primary challenge of clean cooking in underdeveloped countries as outlined by international sustainability targets.

1. Introduction
The Malagasy Island is considered as a global hotspot of biodiversity, with a varied

and unique composition of flora and fauna. The country is estimated to host over 10’000 different species of plants and 800 species of vertebrates, with rates of endemicity over 80% [1]. In recent years, Madagascar has faced challenges in its development, mainly related to environmental degradation, and biodiversity loss, aggravated by factors like deforestation, population growth, and changing climate patterns. The country's biodiversity has become increasingly threatened, with estimates suggesting that Madagascar has lost at least 44% of its forest cover since the 1950s [2]. Widely diffused among the local population, the exploitation of forests for charcoal and fuelwood, mainly for cooking purposes, poses several concerns on both environmental and social aspects. It is estimated that over 11’000 cases of premature deaths, in Madagascar only, can be associated with pollutants and particulate matter substantially related to these daily activities [3]. The growing charcoal industry, coupled with the extension of agricultural land, is expected to accelerate deforestation, amplifying the impacts of climate change on a continent with a lower level of resources to handle such challenges [4]. The CHAR:ME project aims to propose and implement a sustainable loop to decrease the dependence on fuels from primary forests. This project is aligned with the United Nations’s Sustainable Development Goals, encompassing health, clean energy, sustainable cities, responsible consumption, climate action, and life on land.

2. Biomass waste characterization

Focusing on the urban context of Hell-Ville, located on the northern island of Noisy Be, the best sources of available biomass wastes were identified. These mainly included wood shavings and sawdust, but also paper and cardboard, generated by the local carpentry activities. The elemental composition was determined for 5 different samples of local sawdust and for 15 different species of available biomasses. The analyses were performed through a Costech ECS Elemental Analyzer mod. 4010, which allowed for the contemporary measurement of C, H and N content for the samples; O content was determined by difference. Table 1 reports the measured composition of the 5 sawdust samples. Proximate analysis was performed using thermogravimetric analysis (TGA) using a Perkin Elmer SDT Q600. Tests between 30 and 900°C, with a temperature ramp of 10°C/min, both in oxidizing (using air) and inert (using nitrogen) conditions. Through these experiments, it was possible to determine volatile matter, fixed carbon, moisture, and ash contents for all the aforementioned samples. Fig 1. reports the mass loss versus temperature profiles in the presence of nitrogen: all the samples presented similar behavior in these conditions, with an average char yield of 20.71%.

3. Biomass briquetting process

Due to the problems related to the chip-like raw material (e.g., loss of materials during transportation, lower capacity of pyrolysis/gasification processes) and to facilitate processing the feedstock is assembled into briquettes. Through drying and mechanical compression processes, pellets of different dimensions were created

Table 1. Elemental composition of the collected samples (*composition DAF).

Sample	N (wt.%) *	C (wt.%) *	H (wt.%) *	Ash (wt.%)	Moisture (wt.%)
Sawdust_01	0.21 ± 0.02	44.48± 0.2	6.73 ± 0.5	0.00	0.49
Sawdust_02	0.15 ± 0.02	45.60 ± 0.2	7.70 ± 0.5	0.01	0.55
Sawdust_03	0.14 ± 0.02	47.1 ± 0.2	7.18 ± 0.5	0.19	0.60
Sawdust_04	0.37 ± 0.03	45.65 ± 0.2	6.67 ± 0.5	0.69	0.59
Sawdust_05	0.18 ± 0.01	48.81 ± 0.2	7.26 ± 0.5	0.00	0.56

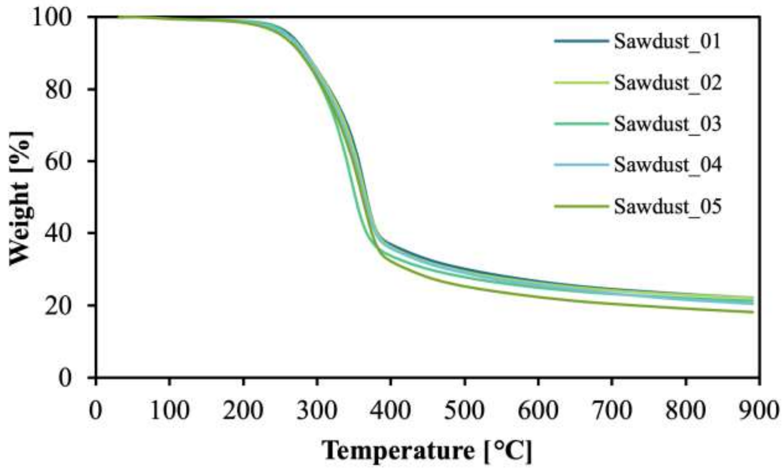

Figure 1. Mass loss profiles of the 5 sawdust samples with nitrogen.

starting from the raw materials previously analyzed. Furthermore, the possibility of mixing other types of available raw materials, such as paper and tapioca starch, was explored in order to increase the mechanical properties of the biomass briquettes. A total of 13 different compositions and compression pressure combinations were tested to find the optimal solution. Considerations about the size of biomass briquettes for improved process efficiency (i.e., for heat and biochar production), while considered as a primary project objective, is outside the scope of this study.

4. Particle Scale Modelling

The elemental analysis of the biomass samples allowed for estimating their chemical compositions, primarily in terms of cellulose, hemicellulose, and lignin, according to the approach by Ranzi et al. [5]. CRECK semi-detailed kinetic mechanism was used to predict the degradation behavior and pyrolysis products distribution. A 0D physical model disregarding heat and mass transfer phenomena was firstly used. Fig 2. reports the predicted curve (line) versus the experimental data (symbols) of the TGA experiments. The model correctly predicts the overall behavior of the samples, properly capturing the initial degradation (mostly due to hemicellulose and cellulose) with some shortcomings in the estimation of the char residue.

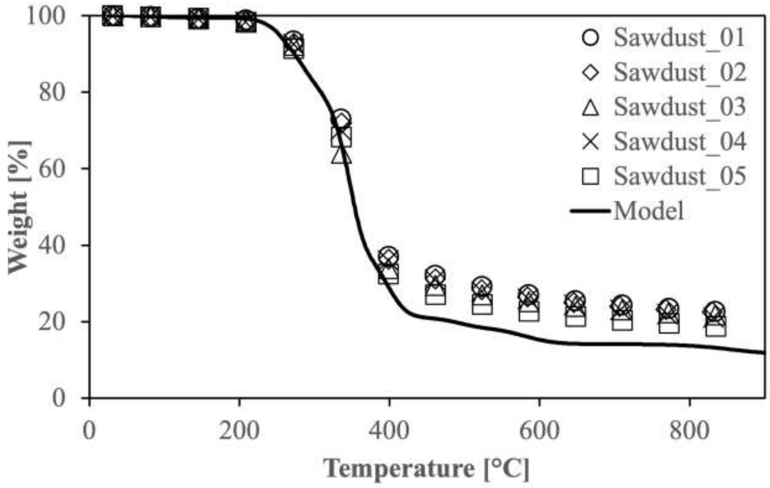

Figure 2. 0D model predictions vs experimental measurements.

The model was then coupled with a 1D isotropic spherical particle model to consider secondary gas-phase reactions and heating behaviors, allowing therefore address more rigorously the biomass briquette behavior. Fig 3a. shows the mass loss curves for a particle of 20 mm diameter considering different temperatures of the environment surrounding the briquette. Fig 3b reports instead the temperature at the core of the particle: the model shows e the expected overshot characteristic of particle-scale biomass degradation, which is due to exothermic charring reactions [6]. Furthermore, both in the 0D and 1D cases, it was possible to evaluate the product distribution and their relative yields, thanks to the detailed chemistry involved within the kinetic scheme.

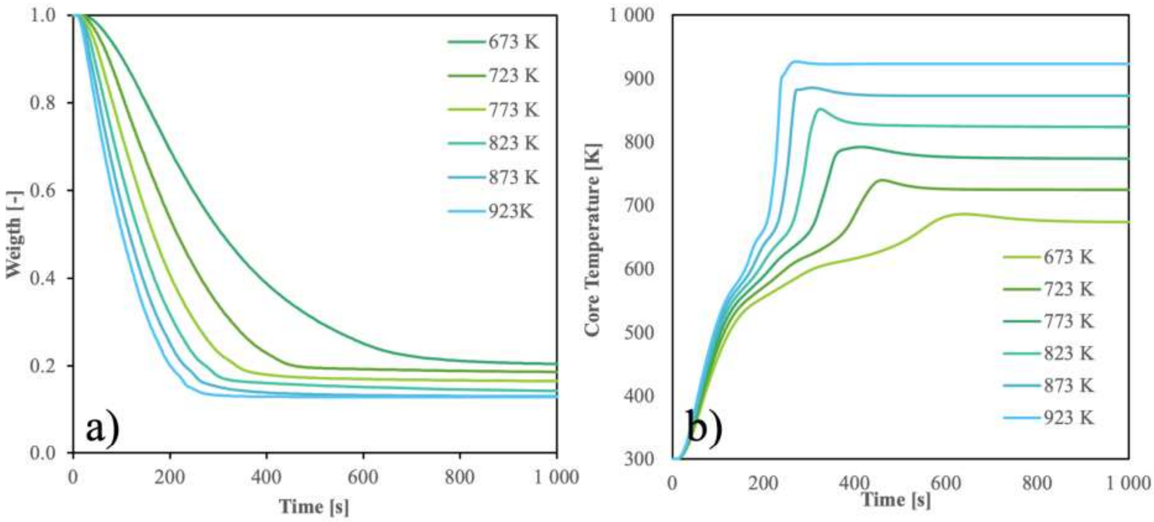

Figure 3. a) mass loss profiles and **b)** Core temperature at different external conditions

5. Pyrolytic hoven

The optimal solution for the design of the pyrolytic hoven is inspired by a "top-lit-up-draft" (TLUD) configuration [7]. A TLUD gasifier stove mainly includes two air inlets: the first is located near the bottom, while the second is near the top, above the level of the loaded biomass. The fire is started at the topmost part, near the first air inlet; after a short ignition time, the oven moves into pyrolysis conditions, forming char and burning the tar fraction produced. As a result, beside a very stable and clean flame, the oven also produces biochar, which can be further utilized as fuel or stored for other needs. Through efficient air management, the production of pollutants is minimized, making it a far safer alternative than the current uses and currently available technologies (e.g. open fire, clay stoves with poor air and heat management). The technology is easily exploitable locally as the stove can be constructed from simple materials and scraps that are commonly accessible. The oven could easily allow for efficient char gasification by opening the bottom air vent and igniting the residual biochar, producing more clean thermal energy. However, since collecting the biochar is the main goal of this stove, we stop the reactor operations at the end of the pyrolysis step. Preliminary full-scale CFD reactor simulations were carried out. These models allow assessing the effects arising from a variety of fluid flow patterns (e.g. as resulting from shape and characteristic size of briquettes), non-uniform temperature distribution as from heat transfer resistances, and governing chemical reactions in the real device. Experimental measurements at the reactor scale are being performed on a stove prototype to validate the accuracy of the coupled CFD/chemistry models predictions and to further confirm the operational efficiency of the reactor.

6. Biochar Analysis

The previously mentioned (in Section 3.) 13 briquettes were pyrolyzed in the real scale reactor, collecting the residual biochar and analyzing it as in Section 2. obtaining data on TGA degradation profiles and elemental composition for all the samples. Additionally, the same analyses were performed on 3 samples of currently used Malagasy charcoal. From the elemental analysis it was possible to estimate the higher heating value (HHV) of the biochar using the Dulong correlation [8], here reported in Fig. 4. Estimates showed that the biochar produced by the pyrolysis oven has similar performance to the currently used charcoal, making it a suitable substitute for these applications. Furthermore, the use of the proposed oven allows for recovery of the heating energy lost in the charcoal production process, allowing also to further reduce the quantity of biomass used for the cooking activities.

7. Conclusions

The CHAR:ME project targets the design of a new pyrolytic stove for the contextual production of thermal power for cooking purposes and biochar in Sub-Saharan Africa. Moving from the assessment of fundamental physicochemical aspects such as biomass feedstock characterization and chemical kinetics of degradation this work presented preliminary results from the multiscale workflow to design an efficient apparatus, enabling the implementation of new sustainable technologies in underdeveloped countries. During the development of the project, characterization

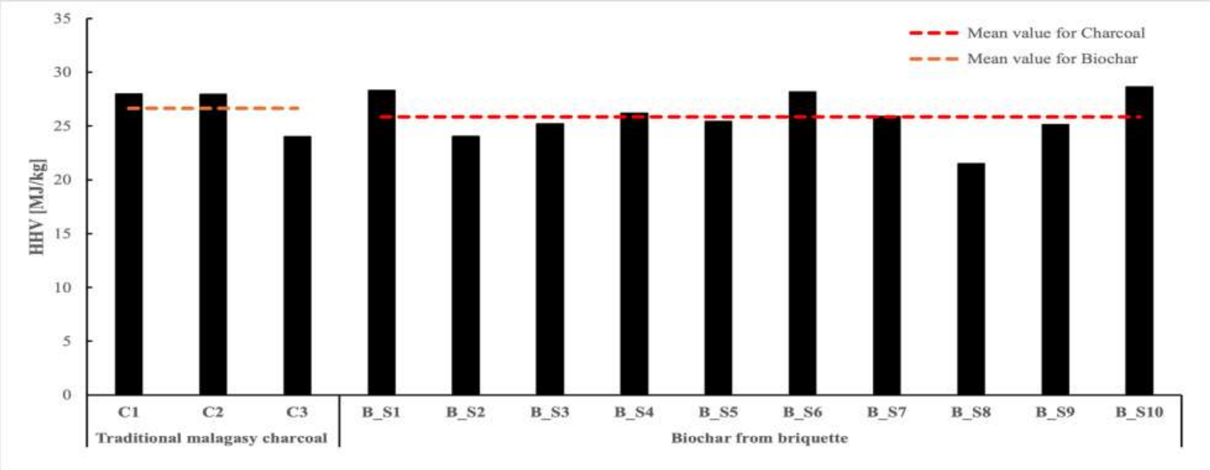

Figure 4. Estimates of the HHV of the analyzed biochar samples

data on many biomasses waste was collected. The use of kinetic models allowed for the prediction of the briquettes' behavior. Full scale reactor CFD simulations and experiments allowed to detect and correct bottle necks on the reactor design. Additional modelling activities (e.g. chemical reactor network) will specifically address flame properties and emissions of NOx and particulate matter to proof the beneficial effects of the proposed technology.

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