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Research Article

Performance, Emissions, and Suitability for Mass Production of an Updraft Biomass Gasifier Cookstove: An Experimental Study

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Abstract

In Cameroon, renewable energy promotion is a key strategy for improving energy security and fostering employment opportunities. This study evaluates the performance, emission levels, and suitability for promotion for mass production of a novel updraft gasifier biomass cookstove. The assessment, conducted using WBT 4.2.3 protocol, focused on thermal efficiency, carbon monoxide (CO) emissions, particulate matter ($PM_{2.5}$) emissions, and safety, in accordance with ISO/IWA Tier 4 standards. $PM_{2.5}$ emissions were prioritised due to their significant health impacts. A Multiple Criteria Decision Analysis (MCDA) was used to assess the cookstove's potential for mass production, considering criteria such as manufacturability, scalability, fuel savings, usability, durability, maintainability, portability, cost/affordability, safety, weight, space, and cultural acceptability. The Results showed that the stove achieved Tier 2 thermal efficiency (≈25%). Indoor air quality tests revealed Tier 2 CO emissions at both low and high power, while $PM_{2.5}$ emissions met Tier 3 at high power and Tier 2 at low power. The safety score was 59/100, corresponding to Tier 1. Compared to the traditional 3-stone fire, the stove demonstrated superior efficiency, indoor air quality, specific fuel consumption, and safety. In the MCDA evaluation, the stove ranked second among five models, confirming its suitability for commercial-scale production, although continuous improvement is required. This study highlights the potential of the first updraft gasifier biomass cookstove tested in Cameroon to contribute to sustainable energy solutions.

Keywords

Improved Cookstove, International Workshop Agreement, Water Boiling Test, Emissions

1. Introduction

The steady growth of the world's population has led to increased demand for basic household needs such as energy, water, and communication services [1]. In sub-Saharan Africa, more than 80% of the population relies on solid biomass - such as firewood, charcoal, agricultural by-products, and animal waste - for cooking and lighting [2]. In Cameroon, biomass accounted for 74.22% of the country's total energy consumption in 2018, amounting to 7.41 Mtoe [3]. As in many developing countries, a major challenge in Cameroon is finding sufficient, environmentally friendly sources of energy. The promotion of renewable energy is central to the country's strategy to improve energy security and create employment

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opportunities.

Most of this biomass fuel is wood, burned in traditional three-stone fires. However, some households also use liquefied petroleum gas (LPG), which has become increasingly inaccessible due to shortages and price hikes since August 2022. This has forced many urban households to revert to traditional cooking methods using wood and charcoal [4]. These three-stone fires are inefficient and produce large amounts of smoke, equivalent to burning 400 cigarettes per hour [5, 6]. Prolonged exposure to this smoke can cause serious health problems, including respiratory infections, eye damage, heart disease, and lung cancer. In 2016 alone, exposure to particulate matter from all sources of air pollution caused approximately 15,000 deaths and 650,000 disability-adjusted life-years lost [7].

To address these challenges, entrepreneurs developed the Tegomo gasifier stove as an alternative cooking solution. Although LPG is considered more environmentally friendly than biomass stoves, its high cost and limited supply make it inaccessible to many. Designed to provide a safer and more sustainable option, the Tegomo stove currently lacks test results to assure customers that it meets national or international regulatory standards [6]. Furthermore, there is no scientifically determined quality, reliability, or performance index to support its effectiveness. This research aimed to evaluate the performance and emission levels of the Tegomo biomass gasifier stove using ISO/IWA Tier 4 standards, and to compare its effectiveness with other cookstoves. The promotion of renewable energy, including stoves like the Tegomo, is key to Cameroon's energy security plan and providing job opportunities in the country.

2. Materials and Methods

2.1. Water Boiling Testing Protocol

The Water-Boil-Test (WBT) version 4.2.3 [8] was conducted to assess stove performance in a controlled manner. The WBT that is one of the most commonly used cookstove comparison test [9]; it consists of three phases: cold-start high-power phase, hot-start high-power phase and simmer phase that immediately follow each other.

For the cold-start high-power phase, the tester begins with the stove at room temperature and uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot (usual 5 L). An emissions hood captures all stove emissions, extracting CO, CO_2, and $PM_{2.5}$ for analysis. The tester also records the mass of the wood required to bring the water to a boil. The cold-start section ends once the water reaches the local boiling temperature. The tester then replaces the boiled water with a fresh pot of ambient-temperature water to perform the second phase [10].

The hot-start high-power phase is conducted after the first phase while stove is still hot. Again, the tester uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. Repeating the test with a hot stove helps to identify differences in performance between a stove when it is cold and when it is hot. This is particularly important for stoves with high thermal mass, as users may keep these stoves warm in practice [10].

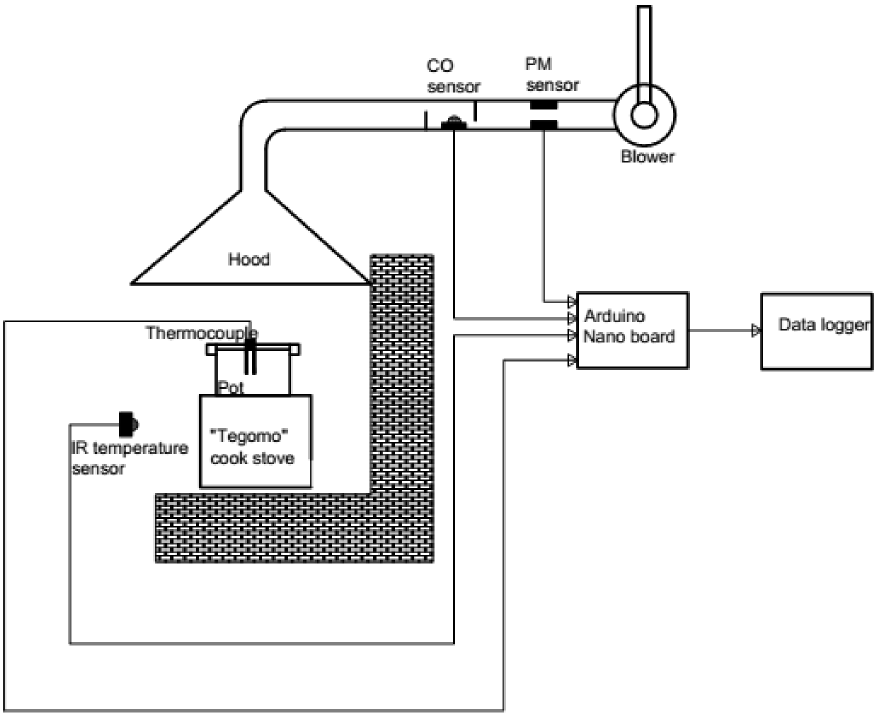


Figure 1. Apparatus for performing the water boiling test.

Figure 2. Water boiling testing setup.

The simmer phase provides the amount of fuel required to simmer a measured amount of water at just below boiling point for 45 minutes. The water is kept near the boiling temperature (± 6°C) for 45 minutes during the simmer phase. Again, the emissions are characterized, and the mass of wood required is recorded. This step simulates the long cooking of legumes or pulses common throughout much of the world [10].

Figure 3. Sensors readings on the LCD.

A testing kit was fabricated (Figure 2) according to the design in Figure 1. We ran tests on it to ensure it is functioning well. The LCD displays five readings (Figure 3) for the five different measurements taken when the cookstove is placed into the testing kit. It shows the $PM_{2.5}$ reading as PM, the carbon monoxide reading as CO, the water temperature (from the thermocouple) as WT, the stove temperature as ST, and the ambient temperature as AT.

The Arduino nano microcontroller collects all the sensor data, processes it and then sends the data to the SD card through the SD card module. This data is logged into the SD card as.txt files (text files) saved into five columns which respectively represents the readings from the $PM_{2.5}$ sensor, carbon monoxide sensor, thermocouple, infrared sensor (stove temperature and ambient temperature). This data can then be extracted and converted into any form for further processing.

The following parameters were evaluated according to WBT version 4.2.3: temperature-corrected time to boil, burning rate, burning efficiency, specific fuel consumption, temperature-corrected specific fuel consumption, fire power, total exhaust flow, mass of CO produced, mass of PM produced, CO emissions per water boiled, and PM emissions per water boiled.

2.2. Cookstove Performance According to ISO/IWA 11: 2012 Standard

To make the results of the water-boiling test meaningful, we classified them according to the ISO/IWA 11: 2012 standard [11], which defines the tiers to which cookstoves can be classified.

The safety tests consisted of the following tests, according to ISO/IWA 11: 2012.

1) The sharp edges and points test involved rubbing a rag over the cookstove to identify and record the number of places where it tears or catches the rag on a table.
2) The team conducted the cookstove tipping test to assess the stove's ability to return to its rest position when tipped. They performed the test four times on each of the stove's four corners without lighting the stove.
3) The containment of fuel test assessed how well the Tegomo gasifier stove prevents fuel spillage when overturned.
4) The obstruction near cooking surface test was conducted to identify any obstacles that could hinder cooking.
5) The surface temperature test evaluates the risk of burns from briefly touching the cookstove surface.
6) The heat transfer to the environment test assessed the risk of the cookstove igniting nearby flammable substances due to heat transfer.
7) The handle temperature test evaluates the temperature of frequently touched parts of the cookstove to assess the burn risk during operation.
8) The chimney-shielding test was not performed on the Tegomo gasifier cookstove as it lacks a chimney, and it was rated the best in this category.
9) The flames surrounding cooking vessel test assesses the burn risk from flames escaping the combustion compartment.
10) The flames exiting fuel chamber test evaluates the cookstove's ability to contain flames when no vessel is placed.

2.3. Controlled Cooking Test

The controlled cooking test (CCT) evaluated the improved stove's performance against traditional models by performing a standard cooking task. It provides two key metrics: (i) fuel consumption per unit weight of food (specific fuel consumption) and (ii) the time required to cook the meal (cooking time).

Table 1 lists the ingredients used for cooking rice, and [12] outline the preparation and procedure for the rice cooking test.

Table 1. *Variable of the CCT.*

Ingredients	Quantity
Dry Rice*	1000 g
Water	1500 g
Salt	10 g
Oil	20 – 30 ml

2.4. Assessment Using Multi Criteria Decision Analysis

A MCDA approach was employed to evaluate the Tegomo cookstove. The evaluation criteria, as identified by Rajabu and Ndilanha [12], were each assigned a weight ranging from 0 to 5, where 0 indicates 'not important' and 5 represents 'very important.' These weights were determined based on the assessment objectives. The relative importance of each criterion was calculated as its weight divided by the total sum of all criterion weights. The overall score for the improved cookstove was derived by summing its scores across all individual criteria. The cookstove was also given a score between 0 – 10. Zero (0), for poor, and ten (10) for excellent, in the criterion. The criterion score was multiplied by respective criterion importance (%) to get Total Score in each criterion. The Overall score is the sum of the Total scores of all criteria Table 2 outlines the proposed weights and the relative importance of each criterion for evaluating the charcoal stove.

Table 2. *MDCA evaluation of Tegomo stove [12].*

Criterion	Rating (0-5)	Importance (%)
Manufacturability and scalability*	5	12.2
Fuel saving	5	7.32
Usability	3	7.32
Durability	5	12.2
Maintainability	2	4.88
Portability	5	12.2
Cost/affordability	4	9.76
Safety-1 (stability, burns)	3	7.32
Safety-2 (emissions)	3	7.32
Weight and space	5	12.2
Looks and cultural aspects	1	2.44
OVERALL SCORE	41	100

Durability test was done according to the durability test protocol prepared by the center for energy development and health at the energy institute at Colorado state university [13, 14]. It consisted of the following tests.

The external impact test evaluated the cookstove's resistance to impacts from transportation, dropped items, or tipping over.

The internal impact test evaluated the cookstove's internal surface resistance to impacts during fuel ash removal or fuel addition.

The quenching test evaluates the cookstove's material resistance to rapid temperature changes due to the temperature difference between the burning flame and the vessel.

3. Results and Discussion

The results from the three phases of the WBT—cold-start, high-power, hot-start high-power, and simmer, after carrying out three tests —are presented in Table 3.

Table 3. *Water boiling test result.*

Variable	Cold start	Hot start	Simmering phase
Temperature-corrected time to boil (min)	45.26	18.55	1998.86
Burning rate (g/min)	11.77	15.30	8.17
Burning efficiency (%)	0.201	0.302	0.328
Specific fuel consumption (g_{fuel}/l_{water})	0.136	0.098	0.098
Fire power (W)	3663.17	4763.43	2543.27
Total exhaust flow (m^3)	141.54	77.72	153.20
Mass of CO produced (g)	27.10	13.17	23.61
Mass of PM produced (g)	0.150	0.013	0.042
CO emissions per water boiled (g_{CO}/g_{water})	0.007	0.004	0.006
PM emissions per water boiled (g_{PM}/g_{water})	1.96E-06	9.59E-07	1.56E-06

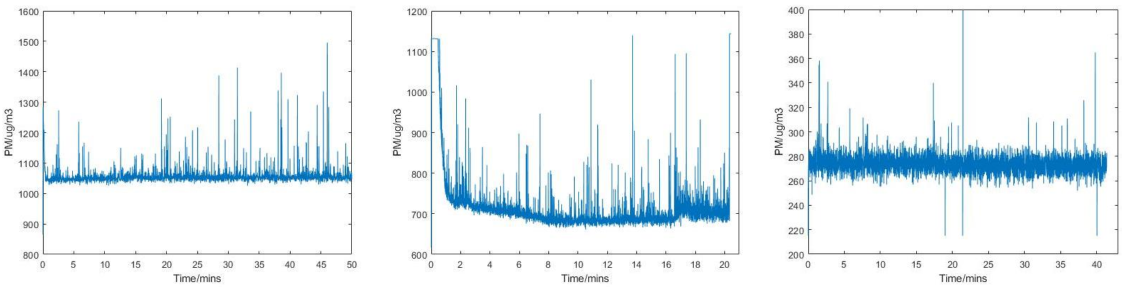
The variations in particulate matter, carbon monoxide, and water temperature over time during these phases are shown in Figures 4, 5, and 6, respectively.

Based on the results in Table 3, we determined the IWA performance characteristics for the Tegomo gasifier cookstove.

This metric allows us to classify the cookstove according to internationally defined standards. The performance metric for the Tegomo cookstove is presented in Table 4.

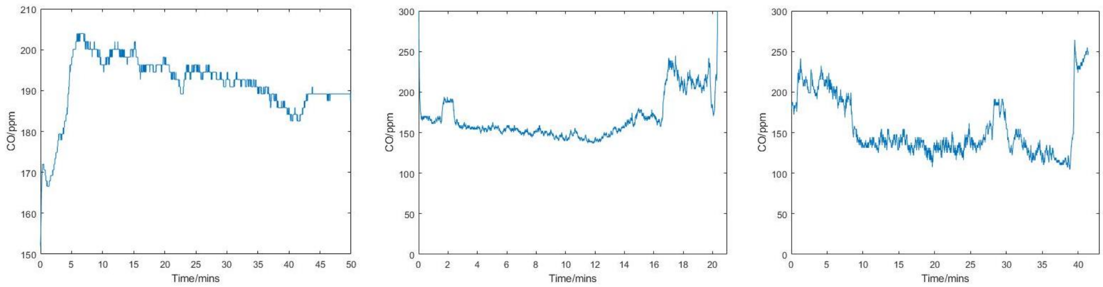
***Table 4**. IWA performance characteristics.*

Characteristic	Units	Average	Average Tier
High power efficiency	%	25	2
Low power specific consumption	MJ/min/L	0.039	2
High power CO	g/MJ_d	10.07	2
High power PM	mg/MJ_d	92.05	3
Low power PM	mg/MJ_d	2.33	2
Indoor Emissions	mg/min	12.1	2



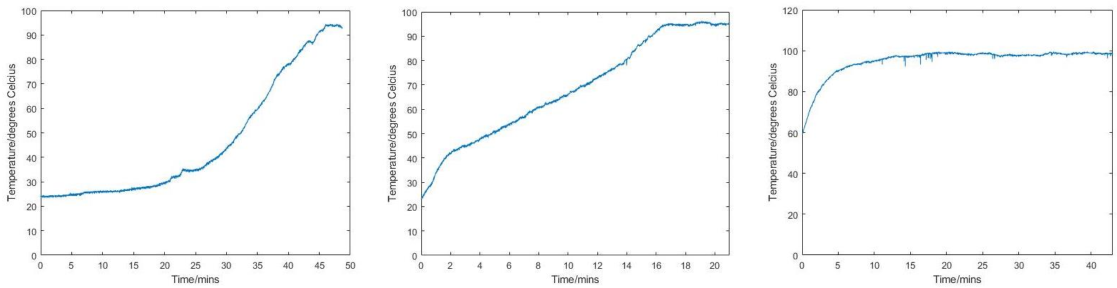
(a) (b) (c)

***Figure 4**. Variation of particulate matter with time in the course of the (a) cold start phase; (b) hot start phase; (c) simmering phase.*



(a) (b) (c)

***Figure 5**. Variation of carbon monoxide with time in the course of the (a) cold start phase; (b) hot start phase; (c) simmering phase.*



(a) (b) (c)

***Figure 6**. Water temperature variation with time during (a) cold start phase; (b) hot start phase; (c) simmering phase.*

The Tegomo stove is in the Tier 2 on most of the metrics but the stove's high power PM output was 92.05 mg/MJ_d, placing it in Tier 3 for particulate emissions. The stove emitted 12.1 mg/min of $PM_{2.5}$ (Tier 2 for Indoor Emissions), significantly exceeds the 2015 WHO Indoor Air Intermediate Guideline of 7.15 mg/min for a vented stove in real use [15, 16].

The Tier 3 for particulate emissions aligns with findings from other studies, such as the performance testing of a natural draft sunken pot rocket stove and side feed bottom air forced draft rocket stove, which reported respectively a High power PM of 152.2 mg/MJ_d and 47.2 mg/MJ_d [10].

We conducted safety tests under controlled conditions to provide reliable, standardized data on the Tegomo stove's safety performance, helping users make informed decisions and take necessary precautions. The key findings from these tests are presented in Table 5. The safety test for the cookstove, as per ISO/IWA 11: 2012, resulted in an overall safety rating of 59/100. Based on this, the Tegomo stove is classified as a Tier 1 cookstove according to the 2015 IWA Tier system.

The controlled cooking test was designed to provide standardized, comparable data for the Tegomo biomass gasifier stove and other stoves, using identical cooking methods and ingredients. This approach ensures that any performance variations are attributed to the stove's design and features.

The controlled cooking test on the Tegomo stove provides valuable data for comparing its performance with four other stoves: the 3-stone fire, Matawi-I, Matawi-Y, and Matawi-Portable as shown in Table 6. The Tegomo stove outperforms the 3-stone fire by 34% in fuel efficiency. It also exceeds the Matawi-I stove, which shows a 26% improvement over the 3-stone fire. However, the Tegomo stove's fuel efficiency is lower than that of the Matawi-Y and Matawi-Portable stoves, which demonstrate 46% and 45% improvements, respectively. Based on these results, the stoves can be ranked according to their performance in the controlled cooking test [17].

The thermal efficiency of the Tegomo stove is comparable to traditional stoves, which can be a significant barrier to adoption [18, 19]. To meet the clean cooking targets of SDG 7 and SDG 13, and to build resilience to climate-related hazards and natural disasters, it is essential to improve the thermal efficiency of the stove to 40-50%. Without this improvement, the achievement of these targets will be severely compromised [18].

Table 5. *Overall safety rating of the Tegomo stove.*

Characteristic	Value	Point score	Test multiplier	Test score
Sharp edges/points	Poor	1	1.5	1.5
Cookstove tipping	Best	4	3	12
Fuel containment	Fair	2	2.5	5
Obstruction near cooking surface	Best	4	2	8
Surface temperature	Poor	1	2	2
Heat transmission to the environment	Poor	1	2.5	2.5
Handle temperature	Poor	1	2	2
Chimney shielding	Best	4	2.5	10
Flames surrounding cooking vessel	Best	4	3	12
Flames exiting fuel chamber	Poor	1	4	4
TOTAL		23/42	25	59/100

Table 6. *Comparative analysis of controlled cooking test results.*

Stove type	Parameter	Cook A	Cook B	Cook C	Mean
3-Stone	Specific Fuel Consumption (g/kg)	239	193	165	199
	Cooking time (min)	25	27	22	24.6
Matawi-I	Specific Fuel Consumption (g/kg)	151	123	165	146
	%-difference with 3-stone	37%	36%	4%	26%

Stove type	Parameter	Cook A	Cook B	Cook C	Mean
Matawi-Y	Specific Fuel consumption (g/kg)	114	102	101	106
	%-difference with 3-stone	52%	47%	38%	46%
Matawi-Portable	Specific Fuel consumption (g/kg)	104	110	108	107
	%-difference with 3-stone	56%	43%	35%	45%
Tegomo-stove	Specific Fuel consumption (g/kg)	144	145	103	131
	%-difference with 3-stone	40%	25%	37%	34%

We conducted durability tests to assess the Tegomo cookstove's structural integrity. Figure 7 illustrates the quenching test, while Table 7 presents the findings from the durability tests performed on the Tegomo biomass gasifier stove. After subjecting the cookstove to five hours of optimum operation, we observed that no major crack on the cookstove materials. The observable change noticed was the decoloration of the outer material around the combustion chamber.

(a) (b)

Figure 7. Cookstove (a) before quenching test (b) afterquenching test.

Table 7. Durability test results.

Characteristic	Tegomo stove
Internal impact test	+0
External impact test	+0
Quenching test	+1
Total	1/17

The results of the internal impact test showed that no change occurred at a maximum mass of 250 g. Referring to the metric for the internal impact test, we deduce that the stove's risk factor for internal impact is +0. Similarly, the external impact test also showed no change at 250 g, leading to a risk factor of +0, according to the external impact test metric [20]. Following the quenching test, we observed only decoloration and minor cracks on the upper part of the stove. Based on the quenching test metric, the stove's risk factor for the quenching test is +1. Similar durability test results were reported for the SSM 26-13 stove under the same protocol [21]. This indicates that the Tegomo stove performs comparably to the SSM 26-13 in terms of durability across all three tests.

After assessing the general characteristics of the Tegomo gasifier cookstove, we obtained the results presented in Table 8; which allowed for a comparative analysis against other cookstoves assessed using MCDA criteria. The Tegomo biomass gasifier stove was compared with clay charcoal, metal-clad charcoal, all-metal charcoal, and gasifier stoves [12].

Table 8. Cookstove evaluation result.

Criterion	General Characteristics	Point score	Total score
Manufacturability and scalability*	Generally, very good for big scale and poor for small scale; Metal expensive and not readily available in rural; Require metal skills and tools	8	0.976
Fuel saving	Good due the insulation that limits waste of heat and gasification process to efficiently extract energy from fuel	9	1.098
Usability	Good since it is capable of using charcoal as fuel	8	0.586
Durability	Poor since some of the metallic parts detoriate when in contact with extreme	5	0.610

Criterion	General Characteristics	Point score	Total score
	charcoal heat		
Maintainability	Poor since it requires metal skills and equipment but less maintenance is required	5	0.244
Portability	Very good (light weight and rigid)	10	1.22
Cost/affordability	Poor (expensive)	5	0.488
Safety-1 (stability, burns)	Very good with stability as it has a wider base Poor as it has hot surfaces	8	0.586
Safety-2 (emissions)	Good as it is a gasification stove	8	0.586
Weight and space	Very good	10	1.22
Looks and cultural aspects	Good	9	0.220
OVERALL SCORE			7.83

In terms of manufacturability and scalability, the Tegomo biomass gasifier cookstove ranks slightly below the metal-clad charcoal and all-metal charcoal cookstoves. The Tegomo stove requires metals that are often not readily available in rural areas, and it requires advanced metalworking skills such as precise cutting and welding. These factors contribute to its lower rating compared to the other stoves. However, the use of metal also has the advantage of reducing manufacturing complexity by eliminating the need for post-processing before use. In addition, the material allows for mass production, with individual parts being produced in batches before final assembly.

In terms of fuel savings, the Tegomo stove ranks just below the gasifier stove, but outperforms other stoves. This is mainly due to its insulated design, with a layer of insulation between the combustion chamber and the outer shell. This insulation minimises heat loss to the environment and ensures that more heat from the burning fuel is effectively used for cooking.

Although the Tegomo stove is a gasifier, it has a single combustion chamber, with gasification taking place in the lower part and complete combustion in the upper part. This simplified design eliminates the complexity of feeding fuel into different stages, making the stove easier to use. In addition, the stove has an elongated removable truck that speeds up the starting process. As a result, it outperforms all stoves except the metal-clad charcoal and all-metal charcoal stoves.

The Tegomo stove is mainly made of metal, except for the insulation, which makes it susceptible to corrosion and reduces its lifespan. As a result, it ranks below the metal-clad and gasifier stoves. However, the use of metal provides resistance to impact, meaning that the stove is less likely to break or deform if dropped or struck by a heavy object. This durability places the Tegomo stove above the clay charcoal stove and on a par with the all-metal charcoal stove.

The Tegomo stove requires minimal maintenance due to its durable metal structure, which is securely welded. The accessibility of its components makes it easy to carry out maintenance if a part fails, contributing to its higher rating compared to other stoves. However, the metal construction can be a challenge to maintain as it requires specialist skills such as metalworking tools. Weighing approximately 5.3 kg, the stove is portable and can be easily carried by one person, making it as portable as the other stoves in the comparative analysis.

In terms of cost/affordability, the Tegomo stove and the gasifier stove are among the lowest. At around XAF 40,000, it may be difficult for a local person to afford compared to other cookstoves. Cost benefits play a key role in the adoption and sustained use of improved cookstoves [18]. In terms of safety -1, the Tegomo stove ranks higher than the clay charcoal and all-metal charcoal stoves. Its square base and conical structure increase stability, making it less prone to tipping, with a maximum tipping ratio of 0.768. However, the handle of the stove can become very hot and can cause burns if touched with bare hands.

For criterion safety-2, the additional gasification process before combustion reduces the total carbon monoxide and particulate emissions. As a result, the Tegomo stove ranks higher than all other stoves except the gasifier stove. It ranks below the gasifier stove because its single combustion chamber limits the rate of gasification, resulting in a comparatively higher emission rate.

Weighing approximately 52 N, the stove is lightweight and easy to carry. It measures 35 cm long, 35 cm wide and 32 cm high, with a base area of 1,225 cm^2 and a volume of 39,200 cm^3. This relatively compact size means that it takes up minimal space in the kitchen. In the appearance and cultural aspects criterion, the stove is painted and visually appealing, which contributes to its high ranking in this category. Based on this comparison, the Tegomo biomass gasifier cookstove ranks second among the five cookstoves, as shown in Figure 8.

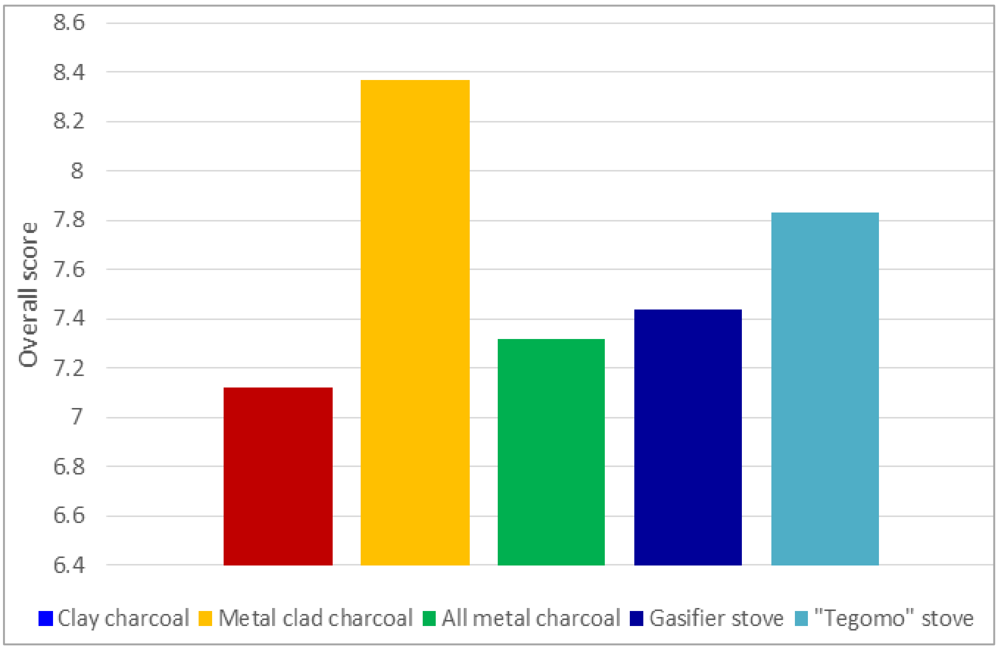


Figure 8. *Comparative overall score of all cookstoves.*

4. Conclusions

The evaluation of the Tegomo gasifier cookstove provides valuable insights into its performance. The results confirm that the stove is a significant improvement over traditional cooking methods in terms of both performance and health impacts. Its thermal efficiency, CO emissions and $PM_{2.5}$ emissions exceed the performance of traditional stoves such as the 3-stone fire. The stove meets Tier 2 standards for thermal efficiency, low and high output CO emissions and $PM_{2.5}$ emissions (Tier 2 for low output and Tier 3 for high output). These results highlight the stove's effectiveness in reducing harmful emissions, which can reduce health risks such as respiratory infections, eye damage and heart disease associated with traditional cooking methods.

These findings highlight key areas for enhancement, particularly in efficiency, emissions, and fuel consumption, to achieve greater efficiency and reduce environmental impact. The MCDA confirms that the stove is suitable for mass production, making it a viable solution for wider adoption to improve cooking efficiency and indoor air quality. These results are of particular value to policymakers seeking to promote cleaner cooking technologies to improve public health and environmental sustainability in developing regions.

5. Recommendations

While the Tegomo stove currently achieves a Tier 1 safety rating, there is room for improvement in several areas where it is rated Tier 2: high power efficiency, low specific power consumption, high power CO, low power PM and indoor emissions. To improve performance, the stove should focus on improving heat transfer and combustion efficiency. Based on the findings of Still et al [15], which highlight performance gaps in stove design - particularly in efficiency, emissions and fuel consumption - targeted improvements in these areas can help optimise the Tegomo stove. These improvements will increase its scalability and overall attractiveness.

Abbreviations

CO	Carbone Monoxide
IWA	International Working Agreement
MCDA	Multiple Criteria Decision Analysis
$PM_{2.5}$	Particulate Matter
WBT	Water-Boil-Test

Author Contributions

Tsapi Tchoupou Kevin: Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Supervision, Writing – original draft

Ndansak Enorran Saam: Formal Analysis, Investigation, Software, Writing – original draft

Bertin Soh Fotsing: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing – review & editing

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Conflicts of Interest

The authors declare no conflicts of interest.

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