Study of combustion characteristics of macadamia shells and coffee husks briquettes in a fixed bed reactor

Apollo Muoki Maingi
Royston M. Kiraithe (kiraitheroyal@gmail.com)
Stephen K. Musau

Research Article

Keywords: Fixed bed, Briquettes, Macadamia shells, Coffee husks, Combustion characteristics

Posted Date: October 30th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3494002/v1

Abstract

In this paper the study was conducted to investigate the combustion characteristics of macadamia shells and coffee husks in a fixed bed reactor. The parameters tested included ignition time, flame propagation speed, mass loss history and temperature flame. Macadamia shell and coffee husk briquettes were produced by mixing with molasses in the ratio of 8:2 and compressed in a mold and piston press at a constant force of 100 K. The briquettes were tested in a fixed bed reactor operated at a constant air mass flowrate of 0.1 kg/s.. The study established that briquettes made from macadamia shells had a higher ignition time of 5.5 minutes compared to the coffee husk which had an ignition time of 2.5 minutes. In addition, briquettes made from macadamia have a lower flame propagation speed of 3.841×10^{-5} m/s compared to the flame propagation speed of coffee husks briquettes which was found to be 1.332×10^{-5} m/s. Macadamia briquettes resulted to higher flame temperatures of 600 ^{O}C compared to coffee husks briquettes 424 ^{O}C when burned in the fixed bed reactor. Therefore, Macadamia briquettes are suitable in small scale application as compared to coffee husk briquettes

1 Introduction

People living in different parts of the world need fuel to meet their day to day needs. Due to worldwide concern regarding environmental impacts and specifically climate change, the use of fossil fuels, volatile fossils fuel market and the need of an independent energy supply to sustain economic development, interest in renewable energy and biomass energy in particular has increased. One of the most common and easily accessible renewable energy resources is biomass which presents a great chance as a feedstock for bioenergy. Biomass resources include; crop residues, wood waste, paper industries, and municipal solid waste among others.

Briquettes are solid fuels that are made through compression of loose biomass materials. Currently briquettes serve as an alternative to firewood, wood pellets and charcoal in developing countries in Africa, Asia and South America. Most raw materials used in this process include chaff from rice, saw dust, peanut and crops waste [1]. Briquettes can be made either with binder or without a binder. Binder prevents the compressed material from springing back and eventually returning to its original form [2]. The natural ligneous material (binder) present in the material helps in bonding [3]. If the residue lacks natural lignin that helps in bonding or the percentage lignin is low, the application of binder will improve the quality of briquettes. The amount and the selection of a binder should be well undertaken to avoid smoke and emission of volatile material that impact human and environment[4]. There are materials that have natural binder, for example, cotton stalks, saw dust, corn stalk, etc. Artificial binder includes far, starch, molasses or cheap organic materials [4]. In the process of briquettes production, binders play a key role which determine their quality and performance [5]. Different binders are used in production of different briquettes. There are different categories in which binders are grouped, which includes inorganic binders, organic binders and compound binders. There are several advantages of inorganic binders which includes low cost, abundant resource, excellent thermos-ability and good hydrophilicity. Ash increased in significant amount is one of the existing challenges of inorganic binders. There are also several advantages of using organic binders which includes low ash, good combustion performance and good bonding. Organic binders have poor mechanical strength and thermal stability because they are easy to decompose and burn when heated and they are expensive. Composite binders consist of at least two binders each playing different role. Compound binders reduces supply of inorganic binders, decrease the cost of organic binders, improved quality of briquettes and improved briquette performance since they can make full use of advantages of all kind of binders. Putting many considerations in briquette process there is no uniform mechanization in briquette manufacturing.

Researchers have undertaken studies on different physio-chemical properties of saw dust briquettes [6]. These properties include moisture content, density, ash content, fixed carbon, volatile matter and calorific value. The rate of conversion of carbon during gasification is affected by moisture content. Low moisture content in a briquette increases the gasifier temperature [7]. According to Mastelerz et.al [8] the product of combustion or gasification is ash and heat, briquettes that produce high ash content are not preferred. There is reduction of heat if the amount of ash produced during combustion is high which leads to reduced efficiency [9].

The technology applied in compressing agricultural waste include piston, screw extruder, pellet press and hydraulic presses [10]. Research has been carried out to investigate the optimum properties and conditions necessary for converting agricultural residue with or without application of binders to make quality fuel briquettes. There are qualities that are required in briquettes as a fuel which includes good combustion, stability and durability in storage and in handling and safety to environment when combusted. There are several measures for these properties [11] which includes; energy value, moisture content, ash content, density or relaxed density, strength, ease of ignition, smoke emissions.

Briquette properties have significant impacts on their combustion and emmission characteristics. The moisture content of the biomass can have a significant impact on its burning properties. According to O'Dogherty et al [12] decrease in briquette stability and density is caused by high moisture content[13]. Due to heat of vaporization, moisture in biomass absorbs heat from the burning fuel during combustion and turns it into vapor, significantly lowering the fuel's ability to provide heat. This may cause the volatile substances to burn insufficiently and deposit unburned carbon (smoke) around the stoves, pots, and pans, making it challenging to clean them. A high moisture level can make ignition difficult. Practically, burning a fuel which has high moisture content leads to production of incomplete combustion byproducts. Ash content affects biomass through lowering its heating value. It also causes problems in the combustion because of the fouling and slagging and its tendency to increase the rate of corrosion on metal in the system[14].

Although there is a lot of literature on briquettes, little is reported on combustion characteristics of briquettes made from macadamia shells and coffee husks. Insight on mass loss history, flame propagation speed, ignition delay on macadamia and coffee husk briquettes is still not clear. This study focuses on mass loss history, flame propagation speed, ignition delay of macadamia and coffee husk briquettes on a fixed bed.

Figure 1: (a) briquette production machine and (b) sample briquettes

2 Methodology

2.1 Briquette Production Process

The raw materials were macadamia shells and coffee husks. The raw materials were collected from Dedan Kimathi University of Technology farm in Kenya. The macadamia shells and coffee husk were left for one week under the sun to dry. They were ground and sieved using sieve number 70 with opening size of 0.21 mm. Molasses was used as the binder. It was preferred over other binders because is cheap and readily available. The ground macadamia shells and the molasses were mixed at ratio of 8:2. The same mixing ratio was repeated for the groud coffee husks with molasses. A digital weighing scale was used to determine the mass ratio of the mixture. The scale had an accuracy of $\pm 0.01g$briquettes were produced using a mold and piston press as shown in Fig. 1(a). All the briquettes used in this study were produced with a pressing force of 100 kN. Samples of briquettes shown in Fig. 1(b). Three experiments were conducted for every parameter tested.

2.2 Experimental set up

Figure 2 shows the experimental set up used. The experiment was carried out on a fixed bed reactor. The system comprised of; fixed bed reactor, temperature data acquisition system and fuel digital weighing scale. The device for combustion is made up of vertical combustion chamber of measurements 750 mm high and an inside diameter of 160 mm. The chamber is made up of four material layers; the inner layer furnace wall, a 40 mm thick refractory cement with thermal conductivity of 0.86 W/m.k [15], a mild steel plate of 2 mm thick and an insulating material 18 mm thick made of aluminum silicate cotton fibber with a thermal conductivity of 0.55 W/m.k [15], at lower temperature up to 400$^\circ C$. All the tests were carried out at a constant air mass flux of 0.1 kg/s.m^2.

2.3 Determination of Combustion Properties

2.3.1 Temperature distribution measurement

Thermocouples were uniformly distributed in the fixed bed at intervals of 79 mm. The temperature was measured throughout the experiment to determine the steady state conditions. Type K thermocouples had chrome as its positive conductor and alumel as its negative conductor and could measure temperature ranging from − 200$^\circ C$ to 1250$^\circ C$ with an accuracy of +-2.2$^\circ C$. The thermocouples were sheathed to protect them. Advantest TR2724 multichannel digital temperature recorder was used in conjunction with the five thermocouples.

2.3.2 Mass loss history

Mass of the fuel bed was continuously monitored. The fixed bed filled with briquettes was placed directly on a digital weighing scale. The digital weighing scale had an accuracy of ± 0.01g. The mass was recorded after every four minutes.

2.3.3 Ignition time

Ignition time was taken as the time taken for the reaction front to start at the briquette surface. It was deduced from the temperature profile. It was considered as the time when the temperature at the fuel surface rise abruptly from ambient value to the peak value.

2.3.4 Flame propagation speed

Flame propagation speed was determined from the temperature measurement and the distance between two adjacent thermocouples using Eq. 1.

$V_f = \frac{\Delta x}{\Delta t}$ ……………………………… (1)

where $\Delta x and \Delta t$ are the distance and time between two adjacent thermocouples where the temparature abruptly rise from the ambient value to the peak value.

2.3.5 Burning rate

The average burning rate of the fuel was evaluated based on mass loss and the combustion time. It was then normalized with the cross-sectional area of the fixed bed.

3 Results and Discussions

3.1 Temperature profile

Figure 3 shows the temperature distribution in the fixed bed reactor for macadamia briquettes (a) and coffee husks (b). Thermocouple reading started at about 26 ^{0}C up to about 600 ^{0}C for macadamia briquettes and 26 ^{0}C up to about 424 ^{0}C for coffee husks briquettes within a range of two minutes. The rise in temperatures showed low deviation from one thermocouple to the next thermocouple in macadamia briquettes compared to coffee husks. The first change was observed from the first thermocouple from the top of the fixed bed reactor to the last thermocouple for both fuels. After the change was recorded in each thermocouple, it continued increasing until it reached the maximum temperature reading.

The high temperature reading for macadamia fuel (600°C) implied that the fuel had lower ash content compared to the coffee husks briquettes fuel (424°C). The small deviation in the temperature rise for macadamia showed that the fuel took more time to burn compared to that for coffee husks briquettes. This implied that most of the fuel mass of the macadamia briquettes was converted to heat energy thus making it a better fuel than coffee husks briquettes. This was attributed to the strong bonds of hydrocarbon which stored more energy in the macadamia briquettes compared to the energy stored in hydrocarbon bonds of coffee husks briquettes.

3.2 Mass loss history

Figure 3.2 shows mass loss history for macadamia shells briquettes and coffee husks briquettes. It shows that the mass of macadamia briquettes was 617 g and 283 g before and after burning respectively while for coffee husks briquettes were 350 g and 225.5 g before and after burning respectively. This implies that the mass that was converted to heat for macadamia briquettes and coffee husks briquettes was 334 g and 124.5 g respectively. This represents 54% and 36% of the converted mass to heat for macadamia briquettes and coffee husks briquettes respectively. The higher heat conversion in macadamia briquettes can be attributed to the good intermolecular bonds which are easily broken during burning as compared to coffee husks briquettes particles.

3.3 Ignition time

The results showed that for a change of temperature to be recorded in the first thermocouple for macadamia shells briquettes, it took five and half minutes while for coffee husks briquettes it took two and half minutes. The calculated ignition time for macadamia briquettes was found to be 5.5 minutes while for coffee husks briquettes was 2.5 minutes. This is attributed to resistivity in ignition for macadamia briquettes due to high moisture content in the macadamia briquettes. It also shows that autoignition temperature of macadamia briquettes are high compared to that of coffee husks briquettes.

3.4 Flame propagation speed

The average flame propagation speed was calculated and found to be 3.841×10^{-5} m/s for macadamia briquettes and 1.3332×10^{-5} m/s for coffee husks briquettes. The coffee husks briquettes have high ignition speed compared to macadamia briquettes. This is attributed to high moisture content in the macadamia shell briquettes.

3.5 Burning rate

The burning rate was calculated and found to be 0.0994 g/sec for macadamia and 0.0371 g/sec for coffee husks. This implies that, high amount of mass of macadamia was converted to energy compared to that of coffee husks. This is attributed to strong bonding between macadamia particles compared to those of coffee husks.

4 Conclusion and Recommendations

The study focused on production and analysis of briquettes made from macadamia shells and coffee husks which are agricultural biomass wastes. The major conclusions from the research were as follows:

- Briquettes made from macadamia shells had a higher ignition time of 5.5 minutes compared to the coffee husk which had an ignition time of 2.5 minutes.

- The study established that briquettes made from macadamia have a lower flame propagation speed of 3.841×10^{-5} m/s compared to the flame propagation speed of coffee husks briquettes which was found to be 1.332×10^{-5} m/s. Macadamia briquettes resulted to higher flame temperatures of 600 ℃ compared to coffee husks briquettes 424℃ when burned in the fixed bed reactor.
- The study established that 54% of macadamia was converted to heat while for the coffee husk briquettes, 36% was converted to heat.
- Therefore, Macadamia briquettes are suitable is small scale application as compared to coffee husk briquettes.

Declarations

Acknowledgement

This work was financially supported by Dedan Kimathi University of Technology, Kenya.

Competing interests: The authors declare no competing interests.

References

1. O. Urbanovičová, K. Krištof, P. Findura, J. Jobbágy, and M. Angelovič, “Physical and mechanical properties of briquettes produced from energy plants,” Acta Univ. Agric. Silvic. Mendelianae Brun., vol. 65, no. 1, pp. 219–224, 2017, doi: 10.11118/actaun201765010219.
2. G. K. Ngusale, Y. Luo, and J. K. Kiplagat, “Briquette making in Kenya: Nairobi and peri-urban areas,” Renew. Sustain. Energy Rev., vol. 40, pp. 749–759, 2014, doi: 10.1016/j.rser.2014.07.206.
3. O. F. Obi, “Evaluation of the effect of palm oil mill sludge on the properties of sawdust briquette,” Renew. Sustain. Energy Rev., vol. 52, pp. 1749–1758, Dec. 2015, doi: 10.1016/j.rser.2015.08.001.
4. A. Kuhe, A. V. Terhemba, and H. Iortyer, “Biomass valorization for energy applications: A preliminary study on millet husk,” *Heliyon*, vol. 7, no. 8, Aug. 2021, doi: 10.1016/j.heliyon.2021.e07802.
5. B. Song, M. Cooke-Willis, B. Theobald, and P. Hall, “Producing a high heating value and weather resistant solid fuel via briquetting of blended wood residues and thermoplastics,” Fuel, vol. 283, Jan. 2021, doi: 10.1016/j.fuel.2020.119263.
6. C. Antwi-Boasiako and B. B. Acheampong, “Strength properties and calorific values of sawdust-briquettes as wood-residue energy generation source from tropical hardwoods of different densities,” Biomass and Bioenergy, vol. 85, pp. 144–152, Feb. 2016, doi: 10.1016/J.BIOMBIOE.2015.12.006.
7. A. T. Eshete, “Production and Characterization of Coffee Husk and Sawdust Briquettes with Potato Peel, Waste Paper and Molasses as a Binding Material,” *Int. J. Sci. Eng. Res.*, vol. 10, no. 8, pp. 1281–1290, 2019, [Online]. Available: http://www.ijser.org
8. A. N. Anozie, O. J. Odejobi, and E. E. Alozie, “Estimation of carbon emission reduction in a cogeneration system using sawdust,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 31, no. 9,

pp. 711–721, Jan. 2009, doi: 10.1080/15567030701752552.

9. R. Kasirajan, “Biodiesel production by two step process from an energy source of Chrysophyllum albidum oil using homogeneous catalyst,” *South African J. Chem. Eng.*, vol. 37, pp. 161–166, Jul. 2021, doi: 10.1016/j.sajce.2021.05.011.
10. C. Martin, F. Starace, and J. P. Tricoire, “The Future of Electricity: New Technologies Transforming the Grid Edge,” *World Econ. Forum*, no. March, pp. 1–32, 2017, [Online]. Available: http://www3.weforum.org/docs/WEF_Future_of_Electricity_2017.pdf
11. X. Song, S. Zhang, Y. Wu, and Z. Cao, “Investigation on the properties of the bio-briquette fuel prepared from hydrothermal pretreated cotton stalk and wood sawdust,” Renew. Energy, vol. 151, pp. 184–191, May 2020, doi: 10.1016/j.renene.2019.11.003.
12. Z. Liu, F. Zhang, H. Liu, F. Ba, S. Yan, and J. Hu, “Pyrolysis/gasification of pine sawdust biomass briquettes under carbon dioxide atmosphere: Study on carbon dioxide reduction (utilization) and biochar briquettes physicochemical properties,” Bioresour. Technol., vol. 249, pp. 983–991, Feb. 2018, doi: 10.1016/j.biortech.2017.11.012.
13. J. O. Chaney, “Combustion characteristics of biomass briquettes,” *Biomass*, vol. 35, no. May, pp. 3884–3890, 2010, [Online]. Available: http://etheses.nottingham.ac.uk/1732/
14. T. Kebede, D. T. Berhe, and Y. Zergaw, “Combustion Characteristics of Briquette Fuel Produced from Biomass Residues and Binding Materials,” vol. 2022, 2022.
15. J. H. I. Lienhard and J. H. V Lienhard, “A Heat Transfer Textbook, fifth edition,” 2020.

Figures

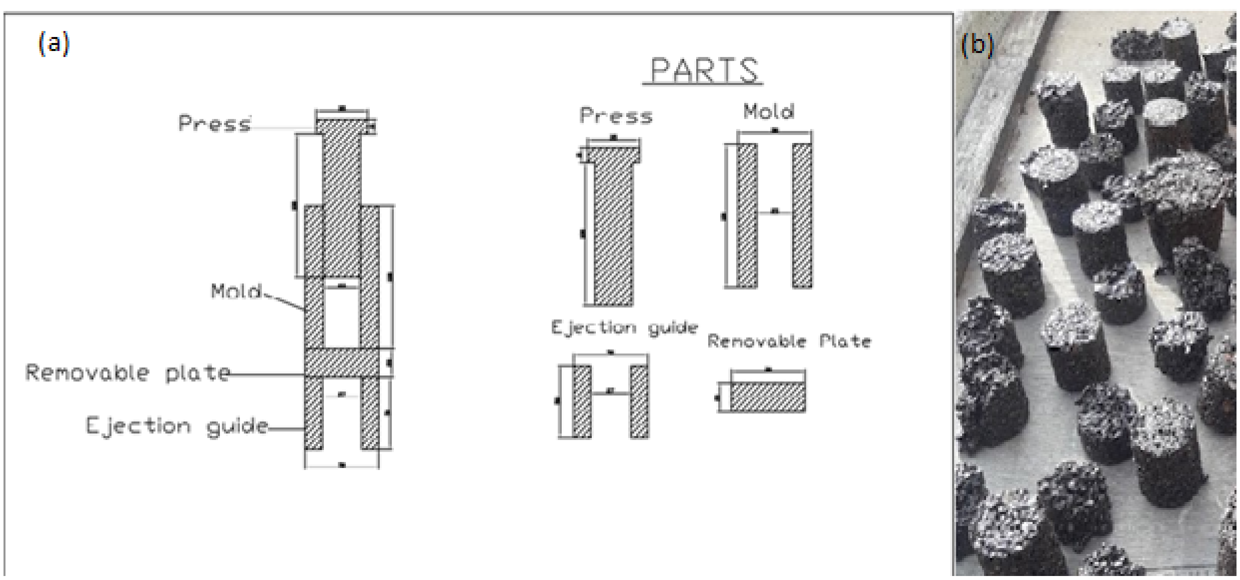

Figure 1

(a) briquette production machine and (b) sample briquettes

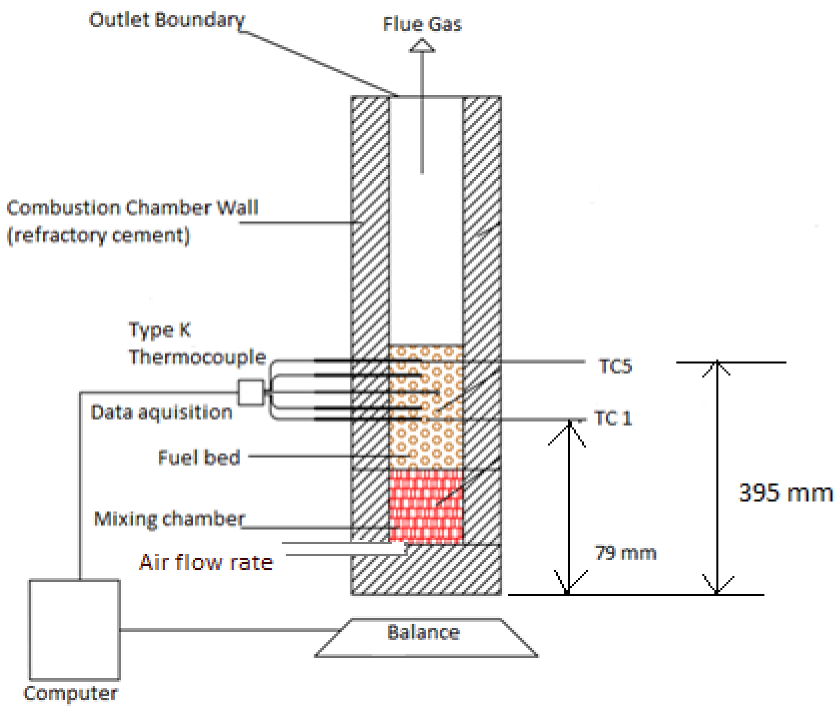

Figure 2

Experimental set up

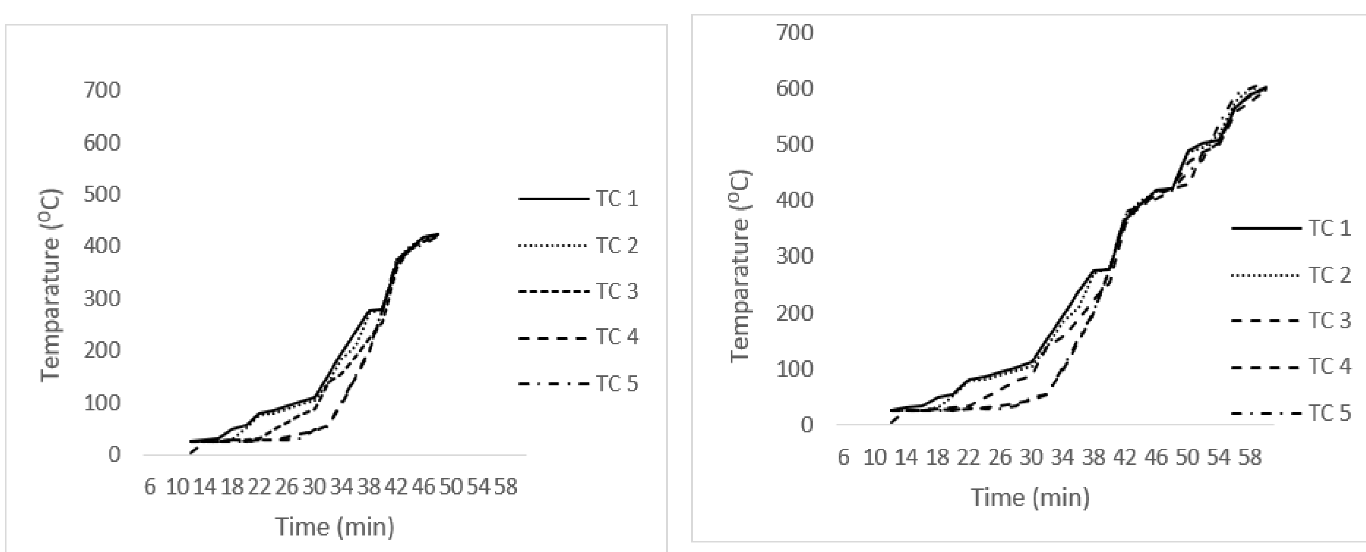

Figure 3

Graphs of temperature distribution in the fixed bed reactor using macadamia briquettes fuel (left) and coffee husks briquettes fuel (right).

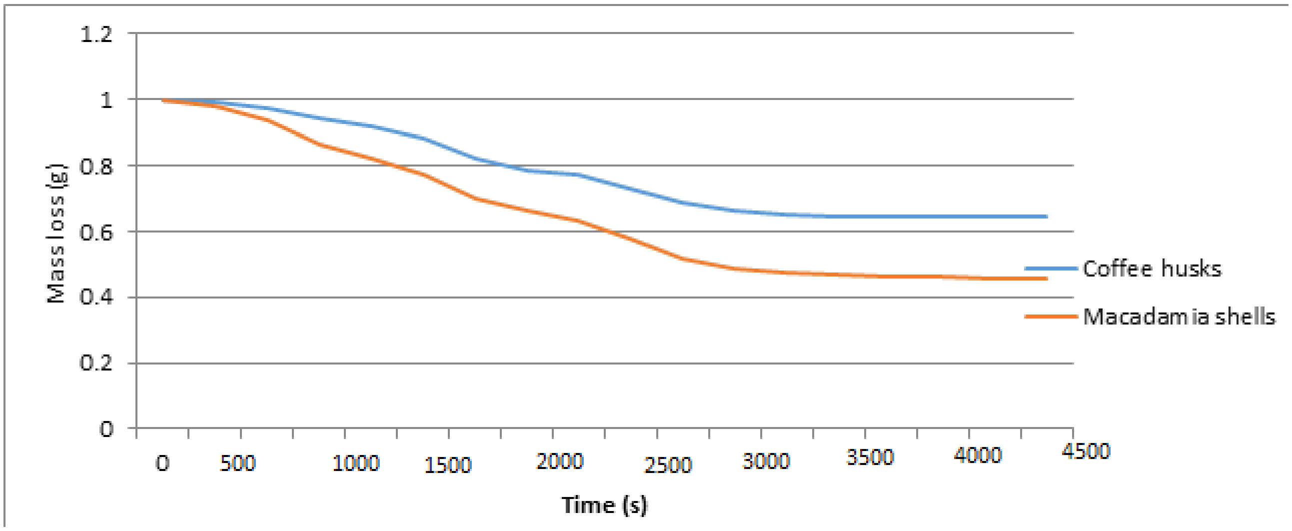

Figure 4

A graph of mass loss history for macadamia shell and coffee husks briquettes