Chemistry Africa (2023) 6:1655–1667
https://doi.org/10.1007/s42250-023-00601-x

ORIGINAL ARTICLE

Assessment of Local Domestic Solid Fuel Sources: A Kenyan Case Study in Kisii, Bomet and Narok Counties

Josephate O. Bosire[1] · Aloys M. Osano[1] · Justin K. Maghanga[2] · Patricia B.C. Forbes[3]

Received: 26 October 2022 / Accepted: 20 January 2023 / Published online: 20 February 2023

Abstract

Proximate analyses and decomposition profiles of solid fuels commonly used in Kenya were studied to determine their relative suitability for use as a clean and efficient source of energy in households. The moisture, volatile matter, ash, and fixed carbon content of firewood, charcoal, and briquette samples were investigated, as well as their decomposition profiles under various temperature regimes. Except for the ash content of the briquette sample, which deviated slightly likely due to the presence of binders, all the values were within acceptable limits according to International Energy Agency and World Health Organization. Decomposition profiles revealed that mass change during combustion tends to occur primarily between 350 and 500 °C once the majority of the volatiles had been released. Briquette samples proved to be the most dependable and suitable household fuel due to their longer combustion time and lower volatile matter content, implying lower emissions.

Keywords Proximate analysis · Decomposition profile · Renewable energy · Household combustion · Solid fuels

1 Introduction

There is currently a surge of interest in renewable energy generally as a result of growing global concern about the environmental consequences of fossil fuel consumption, particularly climate change, and the need for alternative energy production to allow for industrialization. Biomass is a renewable energy source derived from agricultural waste, crop residue, livestock manure, agricultural-based industries and food-processing residue, municipal waste, and other natural products [1]. It was the first source of energy in human history, and it remained the primary global fuel source until the 1800s [2]. Biomass is the fourth most significant primary energy source [3].

Even though traditional forms of energy have significant environmental and health consequences, most developing economies rely heavily on them for cooking, heating, and lighting. The majority of people in the developing world, particularly in Africa, do not have access to modern cooking fuels [4, 5]. As a result, biomass is the primary energy source of choice for these economies. Kenya, for example, uses plant-based biomass fuel as a significant source of energy in rural areas [6]. A wide array of solid fuels are used for cooking and heating in households in developing countries, including biomass and coal [7]. Wood and other solid biomass fuels, including coal, briquettes, dung, farm waste, and grass, are the most common fuels used for cooking and heating purposes in rural areas. Such fuels are mostly obtained from the local community in rural areas and purchased in urban markets [6, 8].

In many underdeveloped countries, the use of raw biomass as a source of energy has a negative impact on health and the environment [9]. In contrast, urbanization is increasing, and the waste generated by these sources may not be responsibly disposed of [10]. In the worst-case scenario, these wastes are burned inadequately, contributing to air pollution [11], although, if properly managed and depending on the waste, they could be renewable sources or energy

✉ Patricia B.C. Forbes
patricia.forbes@up.ac.za

1 Department of Mathematics and Physical Sciences, Maasai Mara University, P. O. Box 861, 20500 Narok, Kenya

2 Department of Mathematics, Statistics and Physical Sciences, Taita Taveta University, P.O. Box 635, 80300 Voi, Kenya

3 Department of Chemistry, University of Pretoria, Private Bag X20, 0028 Hatfield, South Africa

replacements for firewood and charcoal for cooking and other purposes [12].

Solid fuels, such as firewood and charcoal, contribute a more significant proportion of primary energy consumed in Kenyan urban and rural areas. According to Osano et al. (2020) [6], charcoal is mostly used in urban centers, while rural residents prefer firewood solid fuels. According to the study, 21% and 25% of urban populations use firewood and charcoal, respectively, while 28% and 24% of rural populations in Narok and Bomet Counties use firewood and charcoal, respectively, depending on the type of combustion device used [6]. As a result of the growing pace of urbanization, charcoal use has risen rather rapidly [13]. These solid fuels are primarily used in rural and urban regions for cooking, water heating, house heating, lighting, and other domestic activities [14]. The most significant users of wood are domestic households, with small eateries, kiosks, and educational institutions being among the other users [15, 16]. Given the significance of these solid fuels in urban and rural populations, their energy demands necessitate special consideration to maintain long-term viability.

Heating value, chemical characteristics, moisture content, density, hardness, volatile and carbon content, ash content and composition, the melting tendency of ash, and the number of impurities are all factors that influence the attributes of solid fuels [17–19]. Nevertheless, fundamental density and moisture content have been found to be the most critical parameters affecting the qualities of wood as a fuel since they determine the calorific value [20]. Furthermore, tree species cultivated for firewood or charcoal should ideally: grow fast, yield a high amount of wood speedily, and entail minimal management time; blossom well from shoots; generate little and nontoxic smoke when combusted; yield fuel which subdivides conveniently and can be easily transferred; generate other domestic products/services, and produce wood which does not spit or spark while burning.

There has recently been a surge in international interest in the study of technologies that use renewable energy for both environmental and commercial reasons. According to research, biomass resources provide renewable energy that can help enhance current global initiatives to reduce greenhouse gas emissions by partially replacing fossil fuels [21]. Firewood and charcoal derived from various plant species should also be investigated to determine those that emit the least amount of pollutants and are thermally efficient. Furthermore, briquette manufacture from biomass materials and municipal wastes is one of the possible solutions to the aforementioned issues because they can be used as an alternative to firewood and charcoal and may provide a clean energy source [22].

In addition, the decomposition profile trend of solid fuel is related to the mass loss as well as the number of combustion products (emissions) released, allowing combustion to occur (or not). As a result, the connection between solid fuel decomposition and evolved emissions is critical: thermal degradation regulates fuel volatiles/emissions but is dependent on oxidation and temperature distribution, allowing the material to be heated for decomposition [23].

The ability of a tree species to flourish in the region and its rapid growth in these places owing to favorable climatic conditions were the criteria for choosing tree species suited for solid fuel in Narok, Bomet, and Kisii Counties for this study. Acacia is the most favored tree for solid fuel generation in these areas. Nonetheless, because this species has been over-exploited, it would be unable to fully provide the area's fuel demand. As a result, other tree species (*Grevillea robusta, Markham lutea*, and *Eucalyptus globulus*) thought to produce high-quality solid fuels have been used to supplement the acacia. It is on these principles that the suitability of tree species for inclusion in this wood-fuel research was established.

Eucalyptus is the planet's most valued and extensively cultivated hardwood (approximately 18 million hectares) [24, 25]. Eucalyptus is widely cultivated as an exotic plant species across Africa, South America, Asia, and Australia, as well as in relatively temperate areas of Europe, South America, North America, and Australia for timber, charcoal, and firewood [24]. Similarly, *Grevillea robusta* is a fast-growing species that can reach heights of up to 35 m in its natural environment. However, it is more commonly 15 to 25 m tall and has a straight trunk that supports a pyramidal or rounded crown [26]. Due to its rapid growth and increased adaptability to tropical highland conditions, it was introduced decades ago in Kenya as a shade tree to shade crops, including tea and coffee. It is also grown for firewood, charcoal, windbreaks, and beekeeping purposes. Finally, *Markhamia lutea* is an indigenous/native tree found in Kenya's Lake Victoria zone and highland regions (up to 2000 m above sea level). Farmers cultivate this fast-growing yet extensively used agroforestry tree [27]. Markhamia is found as indigenous regenerants in many farmed areas and is safeguarded and typically maintained as pollarded trees. It is now being cultivated as it is among the most valuable tree varieties in this region in practically all forms, services, and products [28]. Timber, poles, posts, fuel wood, furniture, tool handles, medicine (leaves), bee foraging, shade, mulch, decorative, soil conservation, windbreaks, banana props, and tobacco curing are the most common uses of Markhamia. As a result, this research would aid in determining the preferred household solid fuel in terms of moisture content, volatile matter, fixed carbon, and decomposition profiles.

This study used proximate analysis and decomposition profiles to characterize selected commonly used solid fuels (firewood, charcoal, and briquettes) obtained from three Counties in Kenyan; Kisii, Bomet, and Narok, to assess which is the best energy alternative for household use. The findings of this study will assist in mitigating the negative effects of household solid fuel combustion on human health and the environment and encourage the use of the cleanest fuel option. This research is thus directly related to the United Nations Sustainable Development Goal 7 which addresses affordable and clean energy. Furthermore, solid fuels have a high chance of meeting the Kenyan government's target of increasing the percentage of renewables in the country's overall energy mix to a higher level by 2030.

2 Materials and Methods

2.1 Sampling Areas

Kenya is divided into 47 counties, each with its climatic conditions and economic activities. Three counties, Kisii, Bomet, and Narok, were the primary study areas. According to Simons' (2021) clustering analysis on the segmentation of Kenya's 47 Counties, Kisii, Bomet, and Narok counties are in the same geographical and population density category [29]. However, owing to the different climatic conditions in the country, Narok County practices both crop farming and pastoralism. The height and geographical features of Narok County have a significant impact on the climate, with two-thirds being semi-arid. Temperatures range from 20 °C (January-March) to 10 °C (June-September), with an average of 18 °C [30]. The passing of inter-tropical convergent zones influences the amount of rainfall, resulting in a bimodal rainfall distribution. Long rains fall between February and June, whereas short rains fall between August and November. The rainy season brings 2500 mm of rain, while 500 mm of rain falls during the dry season. From March to June, high-intensity rains encourage the growth of flora that serve as food for wild animals.

The lower highland zone of Bomet County receives the most rain, with yearly rainfall ranging from 1000 to 1400 mm [31]. The upper midland region, west of the Rift Valley, receives consistent rainfall, whereas the upper midland region in the county's southern segment receives minimal rain. Temperatures range from 16 to 24 °C [32], with the coldest months being February and April, and the hottest months being December and January. The abundance of water sources and consistent rainfall throughout the year demonstrates why crop and livestock farming is the county's primary economic pursuit.

Kisii County has a highland equatorial climate, which results in a bimodal rainfall distribution with an annual rainfall of approximately 1500 mm [33]. Long rains fall during March and June, whereas short rains occur during September and November, with January and July being generally dry months. The county's highest temperatures range from 21 to 30 °C, with low temperatures ranging from 15 to 20 °C [34]. Crops thrive in the high and reasonably predictable rainfall patterns along with tolerable temperatures. Figure 1 presents the sampling locations in the three Kenyan counties.

The type of solid fuel used in each county is heavily influenced by the various climatic conditions. As a result, the sampling was based on previous studies [6], climatic conditions, and the most commonly used solid fuels in these areas, as described in the Introduction.

2.2 Materials

The samples for the study were solid-fuels (Fig. 2), namely charcoal prepared from different types of trees, fuel briquettes made from waste biomass, and firewood from four distinct tree species namely *Grevillea robusta, Markham lutea, Eucalyptus globulus* (blue gum), and *Acacia auriculiformis*, that are commonly used by communities living in Narok, Bomet and Kisii Counties in Kenya. The *Grevillea robusta, Markham lutea*, and *Eucalyptus globulus* samples were collected from one county (Kisii) where they are commonly used. However, *Acacia auriculiformis* was collected across the three Counties (Narok, Bomet, and Kisii). Moreover, two different briquette samples made of varying concentrations of binders were collected from Narok County where they are commonly used as domestic fuel. Approximately, 5 kg of each sample was collected for this investigation. All the samples were sun-dried and taken to the laboratory for analysis. The ten collected samples were coded accordingly as shown in Table 1 for easy identification and comparison purposes.

2.3 Methods

Approximately 0.5 kg of each sample was ground in the laboratory to finer particles for subsequent investigations. Thermal characteristics of selected solid fuel samples were investigated to ascertain their proximate analysis and decomposition profiles.

2.3.1 Moisture Content

The moisture content was measured using ASTM-D3173 [7, 35]. Ten ground samples (approximately 2.0 g each) were placed in separate alumina crucibles and heated in an oven (Memmert Universal Oven U) at 110 °C for four hours to remove moisture. The crucibles were then cooled to room temperature in a desiccator, and the mass was measured.

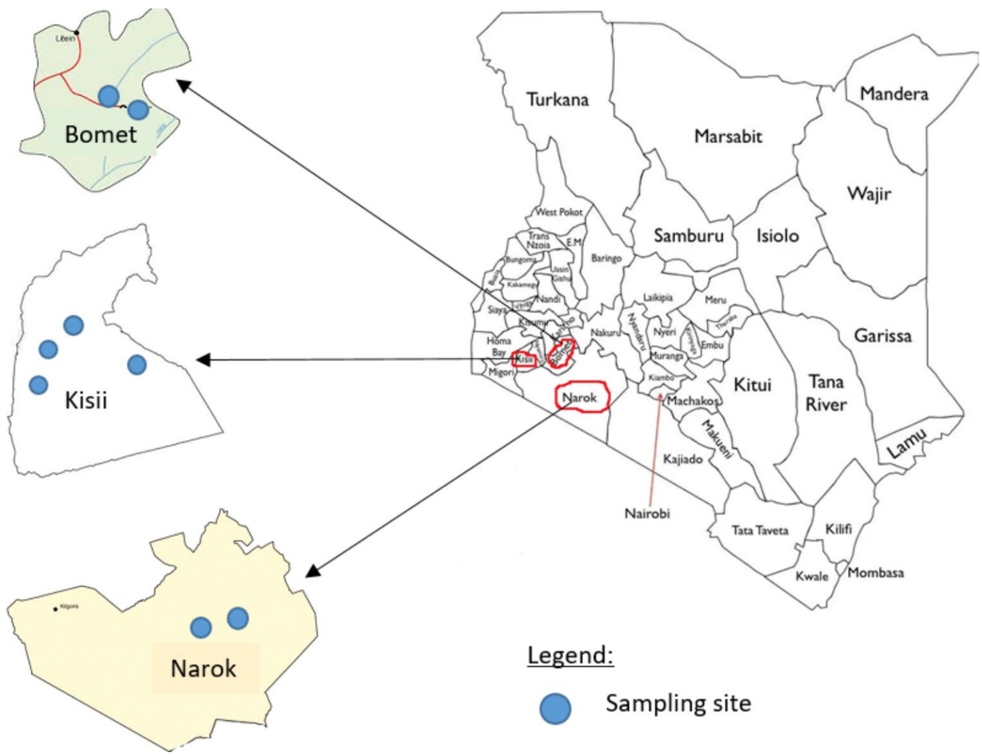

Fig. 1 Map of Kenya showing the sampling points across the three counties of Narok, Bomet and Kisii

The moisture content was computed as a weight loss percentage. Samples were analysed in triplicate for reproducibility and accuracy purposes.

2.3.2 Volatile Matter

The volatile matter was determined using ASTM-D3175 [7, 35]. Moisture-free samples (about 2 g each) were weighed into tared crucibles (supplied by Eisco Labs), capped with lids, and were placed in a muffle furnace (BF1794C supplied by Thermo Scientific Lindberg), and heated to 725 °C for 7 min before being cooled in a desiccator. The crucibles were re-weighed and the percentage mass loss of volatile matter was calculated.

2.3.3 Ash Content

The ash content was evaluated in accordance with ASTM-D3174 [35, 36]. Two grams of the moisture-free samples were weighed into clean crucibles. The uncovered crucibles were placed in a cold muffle furnace and progressively heated to 550 °C for 1 h and then to 700 °C for 2 h. The crucibles were then cooled in a desiccator and weighed. The ash content as a percentage was calculated.

2.3.4 Fixed Carbon Content

The percentage of fixed carbon (PFC) was determined by subtracting the total percentages of volatile matter (PVM), moisture content, and ash content (PAC) from 100.

$$\mathrm{PFC} = 100 - (PVM + MC + PAC) \quad (1)$$

2.3.5 Solid Fuel Decomposition

5 g of each of the chosen samples were heated during various temperature ramps in a muffle furnace to determine the temperature range with the highest decomposition rate. The mass losses from the samples were measured every 50 °C from 100 °C to 700 °C. This was achieved by removing the samples from the furnace, cooling, and weighing their masses after every 50 °C in triplicate. To determine the decomposition profile of the selected samples, mass loss percentages were calculated with respect to the original mass at 50 °C intervals and were represented by temperature versus percentage loss profile plots.

Fig. 2 Investigated solid fuels (wood, charcoal, and briquettes)

Table 1 Solid fuel samples from Kisii, Bomet, and Narok Counties

Sample #	Sample code	Name
1.	KS1-R	*Acacia auriculiformis* – Kisii County
2.	KS2-R	*Eucalyptus globulus* (blue gum) - Kisii County
3.	KS3-R	*Grevillea robusta* - Kisii County
4.	KS4-R	*Markhamia lutea* - Kisii County
5.	KB1-R	*Acacia auriculiformis* – Bomet County
6.	KN1-R	*Acacia auriculiformis* – Narok County
7.	KB2-C	Charcoal sample – Bomet County
8.	KN2-C	Charcoal sample – Narok County
9.	KN3-B	Briquette sample (wheat straw and cut grass, and molasses as binders) - Narok County
10.	KN4-B	Briquette sample (Bargas and waste papers) - Narok County

Table 2 Proximate analysis results of ten solid fuel samples

Sample	Moisture Content (%)	Ash Content (%)	Volatile Matter Content (%)	Fixed Carbon (%)
KS1-R	5.12 ± 0.01	1.19 ± 0.00	88.38 ± 0.33	5.31 ± 0.04
KS2-R	2.40 ± 0.00	1.39 ± 0.01	93.81 ± 0.01	2.40 ± 0.02
KS3-R	4.74 ± 0.02	2.00 ± 0.01	88.53 ± 0.01	4.73 ± 0.16
KS4-R	4.91 ± 0.00	3.69 ± 0.01	86.54 ± 0.01	4.86 ± 0.12
KB1-R	3.45 ± 0.01	5.95 ± 0.05	87.46 ± 0.01	3.14 ± 0.04
KN1-R	3.33 ± 0.01	3.70 ± 0.01	92.84 ± 0.13	0.13 ± 0.03
KB2-C	2.74 ± 0.05	11.57 ± 0.15	20.26 ± 0.59	65.43 ± 0.08
KN2-C	2.07 ± 0.02	19.54 ± 0.10	31.48 ± 0.27	46.91 ± 0.23
KN3-B	2.54 ± 0.01	34.94 ± 0.15	55.46 ± 1.01	7.06 ± 0.17
KN4-B	3.20 ± 0.00	31.67 ± 0.15	51.79 ± 0.12	13.34 ± 0.01

3 Results and Discussion

3.1 Proximate Analysis

Table 2 indicates the results of the proximate analysis for the ten solid fuel samples. The proximate analysis provides the moisture, volatile matter, ash, and fixed carbon content on a dry basis. The fixed carbon reflects the amount of non-volatile organic matter in the samples, which may contain metal oxides (ZnO, PbO, CuO, etc.). The metallic elements (copper, zinc, etc.) are typically derived from the soil during plant growth and development. Heavy metal ions are released into the soil, waterways, and environment as a result of numerous human activities, including agricultural activities such as the use of pesticides, fungicides, and fertilizers. These metals infiltrate the plant system via several physiological processes, and may affect plant growth. Metal oxides may form during the oxidation of the solid fuel during combustion at high temperatures [37, 38]. The presence of metal oxides could have an influence on the non-volatile matter content by increasing the ash content and fixed carbon [4].

3.2 Moisture Content

Moisture content is one of the most important factors in determining the quality of solid fuel, as well as influencing the amount of smoke generated upon combustion. It has a significant impact on the calorific value, the internal temperature of the solid due to endothermic vaporization, and the total energy required to bring the solid up to the pyrolytic temperature value [39]. The sample moisture contents ranged from 2.07 ± 0.02% to 5.12 ± 0.01% (Table 2; Fig. 3).

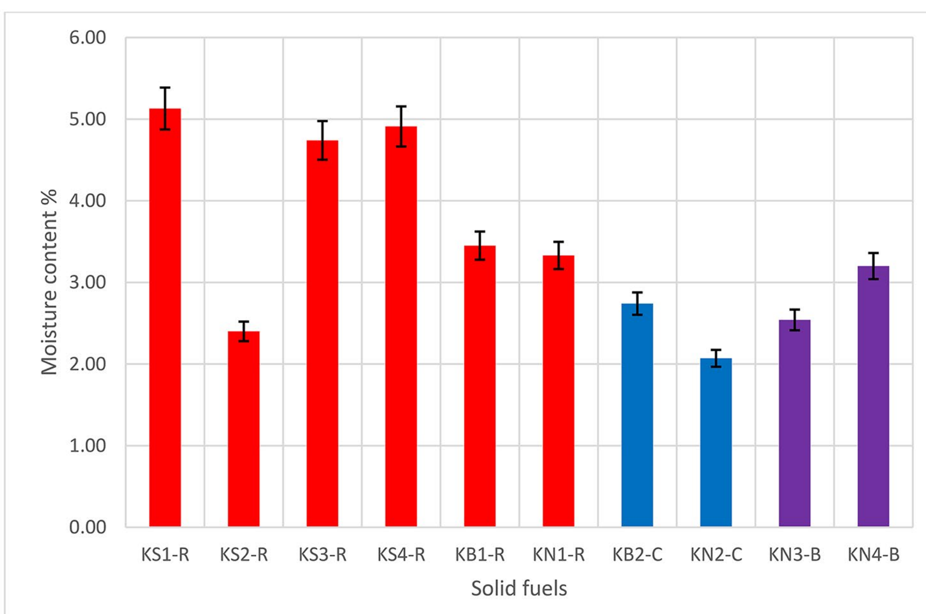

Fig. 3 Moisture content of solid fuel samples: raw biomass (red), charcoal (blue), and briquettes (purple) (n = 3)

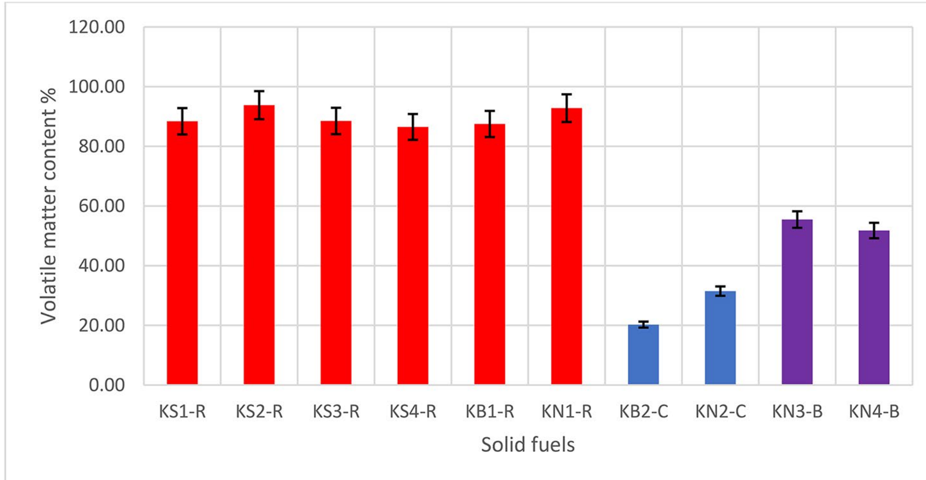

Fig. 4 Volatile matter content of raw biomass (red), charcoal (blue), and briquettes (purple) (n = 3)

Figure 3 shows that KS1-R exhibited the highest moisture content, while KN2-C had the lowest moisture content. All of the tested solid fuel samples from raw plant species, with the exception of KS2-R, have lower moisture contents than charcoal and fuel briquette samples. It should be noted that all samples' moisture contents were within the identified and recommended ranges [40]. In general, fuel briquettes and charcoal samples exhibited lower MC, making them more suitable for use as a form of energy for cooking and many other activities. Lower MC of these fuels implies that they can easily undergo complete combustion, reducing detrimental consequences, such as those arising from smoke generation, to users and the environment [41]. The lower moisture content of briquettes and charcoal could be attributed to the presence of lignocellulosic materials in the components used to prepare them, which is consistent with previous research [42]. On the other hand, combusting high moisture content solid fuels would have a negative impact on both the environment and climate change due to increased emissions of both black carbon as well as brown and organic carbon [41].

3.3 Volatile Matter Content

Volatile matter refers to the substances which have a higher capability to transform into gaseous phase due to weaker intermolecular attractions existing in their structure, thus they can be easily transformed into the vapor phase [43]. This volatile matter refers to the carbon, hydrogen, and oxygen components found in biomass. When heated, the vapor is produced that contains a mixture of short- and long-chain hydrocarbons, oxygenated hydrocarbons, and cyclic and polycyclic aromatic hydrocarbons [44]. According to the literature, the volatile matter content significantly affects the thermal characteristics of solid fuels, particularly charcoal and fuel briquettes, as well as the structure and bonding within the fuels [45]. For example, animal dung has a low volatile content, resulting in smoldering combustion. As shown in Table 2, the proximate results indicate that the volatile matter content for the investigated samples in this study varied significantly from 20.26 ± 0.59% to 93.81 ± 0.01%.

Figure 4 shows that *Eucalyptus globulus* (KS2-R) had the highest VM content (93.81 ± 0.01%), while the charcoal sample (KB2-C) had the lowest (20.26 ± 0.59%). The volatile matter content of the fuel briquette samples was 55.46 ± 1.01% and 51.79 ± 0.12% respectively. However, firewood can have VM contents ranging from more than 60–90% or higher. Moreover, the charcoal samples (KB2-C and KN2-C) showed the least VM contents of 20.26 ± 0.59% and 31.48 ± 0.27% respectively. According to studies, high levels of lignin and low levels of extractives in wood may result in lower levels of volatiles in charcoal and briquettes [46]. High-volatile content fuel briquettes burn quickly but produce a smoky flame, whereas low-volatile content fuel briquettes or charcoal burn slowly but cleanly. As a result, the type of fuel briquettes used is highly dependent on their intended use. For grilling, for example, high-volatile charcoal is preferred, whereas for chemical purification and metal manufacturing, charcoal with a low proportion of volatile matter content is required [47].

3.4 Ash Content

The ash content of different fuels varies, which influences heat transfer and oxygen diffusion to the fuel surface during combustion [48]. Figure 5 depicts the assessment of ash content differences in percentage terms for all prepared samples. Table 2 shows that sample KS1-R had the lowest ash content of all studied samples, at 1.19%. Ash in charcoal and briquettes is typically caused by the presence of inorganic

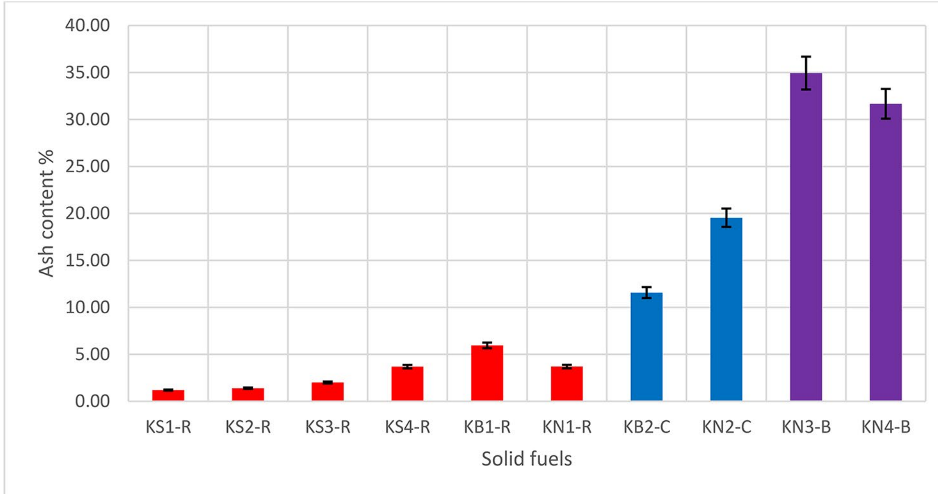

Fig. 5 Ash content of raw biomass (red), charcoal (blue), and briquettes (purple) (n = 3)

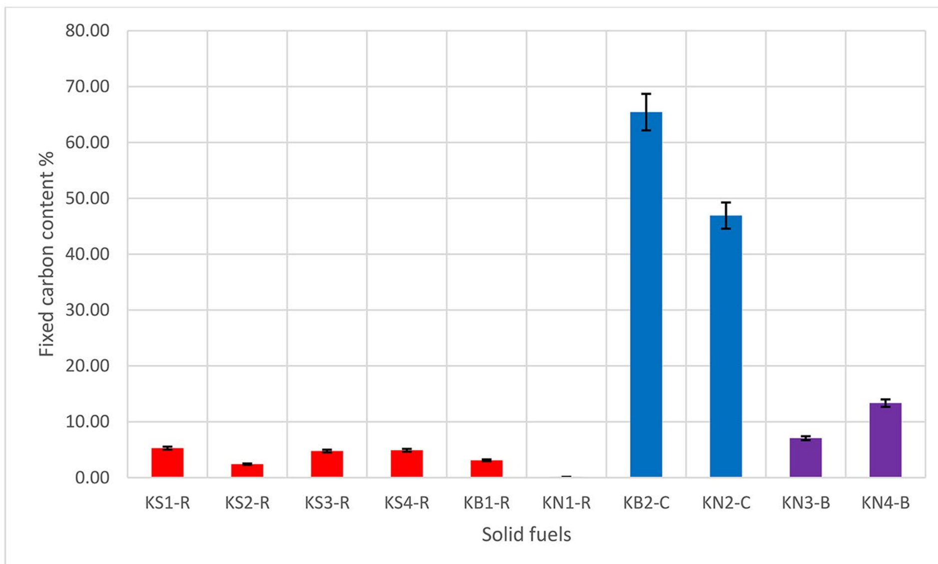

Fig. 6 Fixed carbon content of raw biomass (red), charcoal (blue), and briquettes (purple) (n = 3)

matter that is resistant to degradation during carbonation and therefore remains in the solid fuel as an unwanted residue [49] and this may reduce the heating value of charcoal. The ash content of any solid fuel differs depending on the species of wood and the source of the briquettes.

The composition of binders used in the preparation of fuel briquettes (KN3-B and KN4-B) can also lead to variations in ash content . As a result, as the amount of binders used in briquette preparation increases, so does the ash content of the briquette [36]. As shown in Fig. 5, the ash content of fuel briquettes samples (KN3-B and KN4-B) is higher than the rest of the samples, owing to the presence of binders. The ash content of KN3-B and KN4-B samples is 34.94 ± 0.15% and 31.67 ± 0.15%, respectively. Samples from raw plant species (KS1-R, KS2-R, KS3-R, KS4-R, KB1-R, and KN1-R) contained low ash levels with varying percentages. The low values of ash can be attributed to the absence of binders in the samples [50].

Charcoal samples (KB2-C and KN1-C) had a significant ash content of 11.57 ± 0.15% and 19.54 ± 0.10%, respectively. This indicates that charcoal samples are better fuels than firewood samples because they can burn for a longer period. The ash content of briquette samples (KN3-B and KN4-B) had the highest ash content, followed by charcoal (KB2-C and KN2-C) and finally firewood (KS1-R, KS2-R, KS3-R, KS4-R, KB1-R, and KN1-R) that had the lowest ash content. Briquettes have been shown to be a dependable energy source as a result of their increased mineral matter, which is an implication of the less volatile fuel.

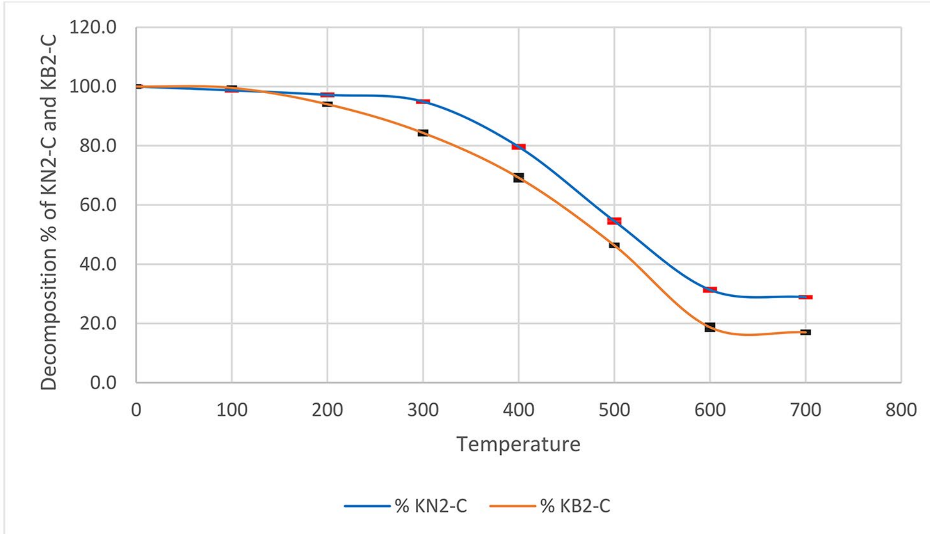

Fig. 7 Decomposition profiles for the charcoal samples (KN2-C and KB2-C)

3.5 Fixed Carbon Content

The proportion of fixed carbon varied across the samples studied (Fig. 6). As a result, all of the samples tested had a fixed carbon content ranging from 0.13 ± 0.03% to 65.43 ± 0.08%. This implies that the samples do not consist solely of fixed carbon, but also of other components that contribute to the volatile matter. The fixed carbon content of fuel briquettes, KN3-B, and KN4-B samples, was 7.06 ± 0.17% and 13.34 ± 0.01%, respectively. Sample KB2-C and KN2-C had the highest fixed carbon contents of 65.43 ± 0.08% and 46.91 ± 0.23% respectively. Contrary, the firewood samples had the lowest fixed carbon contents whereby KS1-R had the highest fixed carbon content of 5.31 ± 0.04%. KN1-R, on the other hand, had the lowest FC of the firewood samples at 0.13 ± 0.03%. The fixed carbon content of a solid fuel is defined as the proportion of carbon accessible for fuel burning after volatile matter has been evolved, and so generally predicts the energy content of a solid fuel, as carbon is the primary heat producer throughout combustion processes [51]. Samples KB2-C and KN2-C, having higher fixed carbon content, are thus considered suitable for thermochemical energy transformation mechanisms. In addition, wood-charcoal matter with minimal fixed carbon content tends to lengthen the heating period due to its modest heat release, as opposed to wood-charcoal matter with high fixed carbon content that produces energy intensely [52]. This observation demonstrates that fixed carbon is an important factor influencing the caloric energy content of a solid fuel, as increased fixed carbon typically equates to increased calorific energy [53].

3.6 Decomposition Profiles of Selected Solid Fuels

The decomposition profile results demonstrated distinct trends of every fuel sample studied with respect to an increase in temperature. The mass of the selected solid fuels decreases as the temperature rises (Figs. 7 and 8, and 9). The decrease in mass, however, is not uniform across all temperature intervals. This could be attributed to the various components of the fuels that volatilize at different temperatures. As a result, the mass decrease is significant at certain temperatures (for example, between 300 and 600 °C, as evidenced by the results (Figs. 7 and 8).

According to the decomposition profile of the charcoal samples, the rate of KN2-C (Narok County sample) and KB2-C (Bomet County sample) decomposition is faster between 300 and 600 °C. This indicates that in this temperature range, more volatiles are emitted, resulting in a significant mass decrease of the fuel sample. The sharp decline in mass corresponds to a sharp drop in char percent yield. Lower temperatures result in lower molecular weight volatile emissions, such as long-chain hydrocarbons, straight-chain carboxylic acids, and other simple but potentially harmful aromatics [54].

Figure 8 depicts a similar trend to Fig. 7 and consists of raw wood sample decomposition profiles. However, the rate of decomposition varies depending on the temperature range. Mass loss of samples KS1-R, KS3-R, and KS4-R occurs dramatically at temperatures ranging from 350 to 500 °C. Furthermore, sample KB1-R exhibits drastic decomposition at temperatures ranging from 400 to 500 °C, whereas sample KN1-R exhibits a sharp decrease at temperatures ranging from 350 to 450 °C. However, KS2-R shows an interesting trend, since it displays two mass loss zones, that is, from 350 to 400 °C and from 450 to 500 °C. This

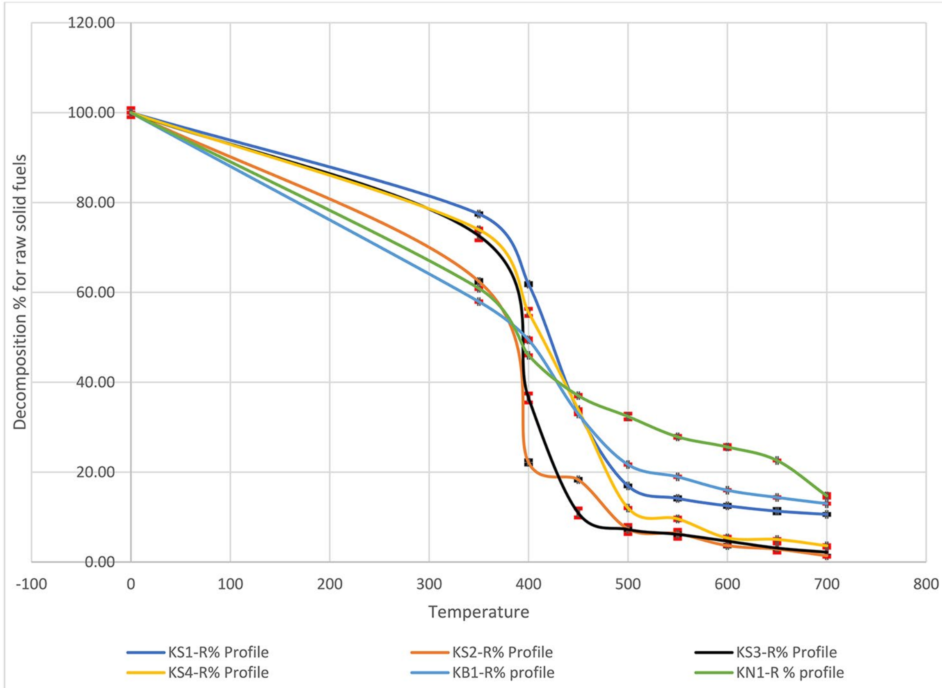

Fig. 8 Decomposition profiles for raw wood samples (KS1-R, KS2-R, KS3-R, KS4-R KB1-R, and KN1-R)

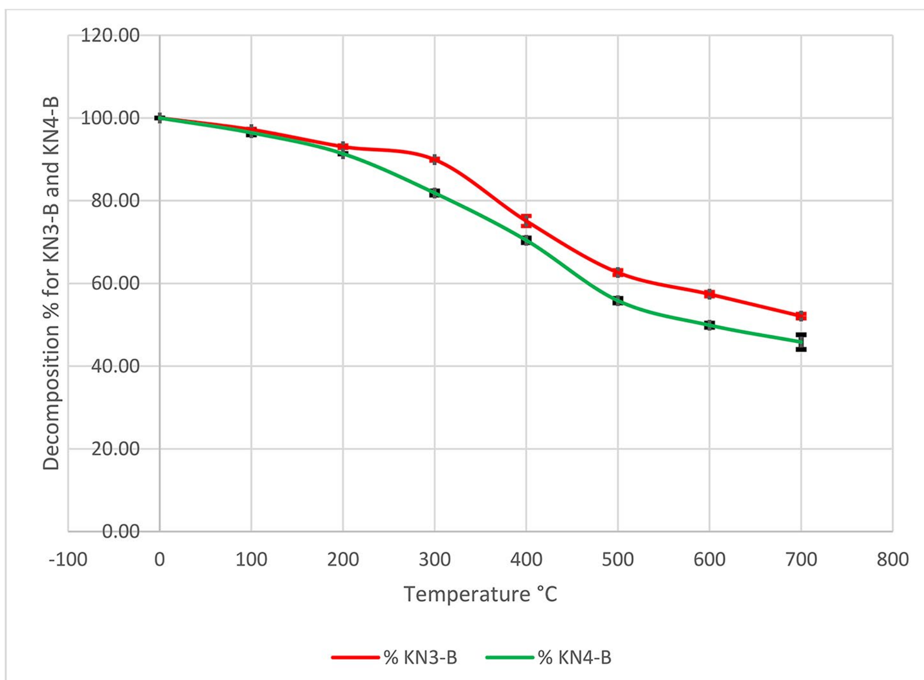

Fig. 9 Decomposition profiles for briquette samples (KN3-B and KN4-B)

could be attributed to the fact that KS2-R has a different moisture content (2.4%), which affects the decomposition profile. The differences demonstrated by samples KS1-R, KB1-R and KN1-R could be attributed to their environment since they are samples of the same species but grown in different Kenyan Counties with varying climatic conditions, which may impact on wood density, for instance.

As shown in Fig. 9, comparing the two briquette samples KN3-B and KN4-B, the decomposition rate appears to be slower than that of samples shown in Figs. 7 and 8. This implies that the samples KN3-B and KN4-B emit at a slow rate over a wide temperature range. Furthermore, at lower temperatures, emission production is much lower than at higher temperatures [55]. These findings are consistent with existing data, which shows that at lower temperatures, fewer emissions are produced, particularly straight-chain hydrocarbons, alcohols, and carboxylic acids [54], which are thought to be relatively harmless unless they undergo oxidative processes.

In general, Figs. 7 and 8, and 9 show that low molecular weight volatile compounds are emitted at temperatures less than 600 °C. However, as the temperature rises above 600 °C, the mass continues to fall, although at a slower rate. This is likely because polycyclic aromatic hydrocarbons, which are typically generated at high temperatures, are released [44]. Between 600 and 700 °C, the percent yield almost flattens, implying that the majority of the emissions have been released from the samples.

4 Conclusion

The purpose of this research was to investigate the effect of proximate properties on the combustion and fuel characteristics of solid fuels commonly used in Kenyan households in the Kisii, Bomet, and Narok Counties. Moisture, volatile matter, ash, and fixed carbon contents were discovered to affect the combustion and fuel characteristics of the solid fuels investigated in this study. The proximate analysis of these solid fuels revealed that *Acacia auriculiformis* from Kisii County had the highest moisture content, whereas the charcoal sample from Narok County had the lowest. The highest ash content was found in the briquette sample (containing wheat straw and cut grass as starting materials, and molasses as a binder), resulting in a higher mineral content. Furthermore, the *Eucalyptus globulus* raw wood sample had the highest volatile matter content ($93.81 \pm 0.01\%$), while a Bomet charcoal sample had the lowest ($20.26 \pm 0.59\%$). The Narok County charcoal sample, on the other hand, had the highest fixed carbon content, while the raw acacia sample from Narok County had the lowest. The higher fixed carbon content indicates that the fuel would then require more time to burn. Similarly, the combustion properties of the examined solid fuels show variations in their decomposition profiles, owing to substantial differences in ash, volatile matter, and fixed-carbon contents, among the solid fuels. In this regard, charcoal and briquette solid fuels burned slowly, whereas firewood fuel types experienced rapid thermal degradation. Consequently, the description of desirable criteria for quality solid fuels is influenced not only by proximate analysis relative to fixed carbon content but also by decomposition profiles. Thus, this investigation has shown the impact of considering combustion and solid fuel quality attributes in addition to calorific value alone in the choice of household fuel usage in Kisii, Bomet, and Narok Counties. As a consequence of their lower volatile matter content, and higher fixed carbon and ash contents, briquettes may be preferred household fuels as they can burn for longer periods while potentially emitting fewer pollutants.

Acknowledgements The authors wish to thank the Department of Animal Science, Egerton University for providing the necessary equipment, assistance, and space for this study.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.
Open access funding provided by University of Pretoria.
Open access funding provided by University of Pretoria.

Data Availability Data will be made available on request.

Declarations

Conflict of Interest The authors declare that they have no conflicts of interest. Patricia Forbes is Associate Editor of Chemistry Africa.

Reference List

1. Ríos-Badrán IM, Luzardo-Ocampo I, García-Trejo JF, Santos-Cruz J, Gutiérrez-Antonio C (2020) Production and characterization of fuel pellets from Rice Husk and Wheat Straw. Renewable Energy 145:500–507. https://doi.org/10.1016/j.renene.2019.06.048
2. Yun X, Shen G, Shen H, Meng W, Chen Y, Xu H, Ren Y, Zhong Q, Du W, Ma J (2020) Residential solid fuel emissions contribute significantly to Air Pollution and Associated Health Impacts in China. Sci Adv 6(44):eaba7621. https://doi.org/10.1126/sciadv.aba7621
3. Malico I, Pereira RN, Gonçalves AC, Sousa AM (2019) Current status and future perspectives for Energy Production from Solid Biomass in the European Industry. Renew Sustain Energy Rev 112:960–977. https://doi.org/10.1016/j.rser.2019.06.022
4. Szymajda A, Łaska G, Joka M (2021) Assessment of cow dung pellets as a renewable solid fuel in direct combustion technologies. Energies 14(4):1192. https://doi.org/10.3390/en14041192
5. McCarron A, Uny I, Caes L, Lucas SE, Semple S, Ardrey J, Price H (2020) Solid fuel users' perceptions of Household Solid fuel use in low-and Middle-Income Countries: a scoping review. Environ Int 143:105991. https://doi.org/10.1016/j.envint.2020.105991
6. Osano A, Maghanga J, Munyeza C, Chaka B, Olal W, Forbes P (2020) Insights into household fuel use in kenyan communities. Sustainable Cities and Society 55:102039. https://doi.org/10.1016/j.scs.2020.102039

7. Shiferaw Y, Tedla A, Melese C, Mengistu A, Debay B, Selamawi Y, Merene E, Awoi N (2017) Preparation and evaluation of clean briquettes from disposed Wood Wastes. Energy sources, part. Utilization and Environmental Effects 39(20):2015–2024. https://doi.org/10.1080/15567036.2017.1399175. A: Recovery
8. Lackner M, Palotás Á, Winter F (2013) Combustion: from basics to applications. Methods, vol 1. John Wiley & Sons, p 4
9. Tripathi N, Hills CD, Singh RS, Atkinson CJ (2019) Biomass Waste Utilisation in Low-Carbon Products: harnessing a major potential resource. Npj Clim Atmospheric Sci 2(1):1–10. https://doi.org/10.1038/s41612-019-0093-5
10. Asmare M, Alelign B (2019) Bahir Dar City Municipal Solid Waste potential Assessment for Clean Energy. Am J Energy Eng 7(1):28–38. https://doi.org/10.11648/j.ajee.20190701.14
11. Munyeza CF, Osano AM, Maghanga JK, Forbes PB (2020) Polycyclic aromatic hydrocarbon Gaseous Emissions from Household Cooking Devices: a kenyan case study. Environ Toxicol Chem 39(3):538–547. https://doi.org/10.1002/etc.4648
12. Board OS (2019) E. National Academies of Sciences, and Medicine, Environmental Engineering for the 21st Century: Addressing Grand Challenges. National Academies Press
13. Petro R, Laswai F, Mijai M, Nyaradani G, Balama C (2015) A review on tree species suitability for wood fuel in Kilimanjaro region. J Environ Earth Sci 5:23–27. https://core.ac.uk/download/pdf/234664185.pdf
14. Endalew M, Belay DG, Tsega NT, Aragaw FM, Gashaw M, Asratie MH (2022) Environ Health Insights 16:1–11. DOI: https://doi.org/10.1177/11786302221095033. Household Solid Fuel Use and Associated Factors in Ethiopia: A Multilevel Analysis of Data From 2016 Ethiopian Demographic and Health Survey
15. Mugo F, Gathui T *Biomass energy use in Kenya*, in *International ESPA workshop on biomass energy*. 2010, International Institute for Environment and Development (IIED): Parliament House Hotel, Edinburgh.Practical Action, Nairobi, Kenya
16. Chisika SN, Yeom C (2021) Enhancing Ecologically Sustainable Management of Deadwood in Kenya's Natural Forests. International Journal of Forestry Research, 2021. https://doi.org/10.1155/2021/6647618
17. Davies RM, Davies OA, Mohammed US (2013) Combustion characteristics of traditional energy sources and water hyacinth briquettes. Int J Sci Res Environ Sci 1(7):144. https://doi.org/10.12983/ijsres-2013-p144-15
18. Akowuah JO, Kemausuor F, Mitchual SJ (2012) Physico-chemical characteristics and market potential of sawdust charcoal briquette. Int J Energy Environ Eng 3(1):1–6. doi:https://doi.org/10.1186/2251-6832-3-20
19. Dizaji HB, Zeng T, Hölzig H, Bauer J, Klöß G, Enke D (2022) Ash transformation mechanism during combustion of rice husk and rice straw. Fuel 307:121768
20. Martinez CLM, Sermyagina E, Carneiro AdCO, Vakkilainen E, Cardoso M (2019) Production and characterization of coffee-pine wood residue briquettes as an alternative fuel for local firing systems in Brazil. Biomass Bioenergy 123:70–77. https://doi.org/10.1016/j.biombioe.2019.02.013
21. Maysyuk E, Kozlov A (2019) Environmental Problems of Solid Fuel Combustion in House Furnaces and Small Boilers and Ways their Solution. in IOP Conference Series: Earth and Environmental Science. IOP Publishing
22. Rominiyi O, Adaramola B, Ikumapayi O, Oginni O, Akinola S (2017) Potential utilization of Sawdust in Energy, Manufacturing and Agricultural Industry; Waste to Wealth. World J Eng Technol 5(03):526. https://doi.org/10.4236/wjet.2017.53045
23. Rogaume T (2018) Thermal Decomposition of Solid Fuels. Objectives, Challenges and Modelling. in Journal of Physics: Conference Series. IOP Publishing
24. Rockwood DL, Rudie AW, Ralph SA, Zhu J, Winandy JE (2008) Energy product options for Eucalyptus species grown as short rotation woody crops. Int J Mol Sci 9(8):1361–1378. https://doi.org/10.3390/ijms9081361
25. Mendoza-Martinez C, Sermyagina E, Saari J, Ramos VF, Vakkilainen E, Cardoso M, Rocha EPA (2023) Fast oxidative pyrolysis of eucalyptus wood residues to replace fossil oil in pulp industry. Energy 263:126076. https://doi.org/10.1016/j.energy.2022.126076
26. Takaoka S (2008) A comparison of the utility and agronomic traits of indigenous and exotic trees in the Mount Kenya region. Small-scale Forestry 7(1):77–85
27. Ombati KR (2018) A study of some factors influencing domestication and adoption of indigenous Tree" Eswata"(Markhamia Lutea) by Communities in Teso north sub County, Kenya. University of Kabianga
28. Muga MO, Owino F, Ruigu S (2014) Variation in wood density and strength properties among Markhamia lutea (sprague) half sib families from western Kenya. Int J Appl Sci Technol 4(4):221–228. http://www.ijastnet.com/journals/Vol_4_No_4_July_2014/24.pdf
29. Simons W (2021) The Segmentation of Kenya's 47 Counties - Spatiality Limited. Spatiality Limited - Big Data and Location Analytics. September 29; Available from: https://www.spatiality.co.ke/the-segmentation-of-kenyas-47-counties/
30. Korir J (2020) Climate change adaptation strategies adopted for sustainable livelihoods by the Pastoral Community in Narok County. Afr Environ Rev J 4(1):54–73. http://www.aer-journal.info/index.php/journals/article/download/105/135
31. Mwangangi CE (2021) *Determinants of Food Crop Diversification among Smallholder Maize Farmers for Enhanced Food Security in Bomet County, Kenya*.
32. Too E, Soi R, Ogali I, Masila E, Nyamache A (2021) Comparative analysis of sugar stabilizers on stability of thermo-tolerant vaccine for viral disease control in small ruminants. East Afr Agricultural Forestry J 85(1–4):8–8. https://www.kalro.org/www.eaafj.or.ke/index.php/path/article/download/523/561
33. Nyagwansa R, Ochola W, Odhiambo J, Bunyatta D, Omweno JO (2021) Effectiveness of selected Advisory channels on safe use of pesticides among the small holder Kale Farmers. A case of Kisii County, Kenya. East Afr J Agric Life Sci 4(6):151–156. https://doi.org/10.36349/easjals.2021.v04i06.003
34. Akunga G, Njiru J, Getabu A (2018) Effect of pond type on physicochemical parameters, phytoplankton diversity and primary production in, Kisii, Kenya. International Journal of Fisheries and Aquatic Studies. http://41.89.141.8/kmfri/bitstream/123456789/857/1/Akunga18.pdf
35. Nadkarni R (2014) Elemental analysis of Fossil Fuels and related materials. ASTM International West Conshohocken, PA, USA
36. Kozlov A, Svishchev D, Donskoy I, Shamansky V, Ryzhkov A (2015) A technique Proximate and Ultimate Analysis of Solid Fuels and Coal Tar. J Therm Anal Calorim 122(3):1213–1220. https://doi.org/10.1007/s10973-015-5134-7
37. Zhang C, Zhang L, Li Q, Wang Y, Liu Q, Wei T, Dong D, Salavati S, Gholizadeh M, Hu X (2019) Catalytic pyrolysis of poplar wood over transition metal oxides: correlation of catalytic behaviors with physiochemical properties of the oxides. Biomass Bioenergy 124:125–141. https://doi.org/10.1016/j.biombioe.2019.03.017
38. Staničić I, Brorsson J, Hellman A, Mattisson T, Backman R (2022) Thermodynamic analysis on the Fate of Ash Elements in Chemical Looping Combustion of Solid Fuels Iron-Based Oxygen Carriers. Energy Fuels 36(17):9648–9659. https://doi.org/10.1021/acs.energyfuels.2c01578
39. Azman NAM, Pa NFC (2021) Production of Smokeless Biofuel Briquettes from Palm Kernel Shell assisted with slow pyrolysis

treatment. Progress in Engineering Application and Technology 2(1):38–49. https://doi.org/10.30880/peat.2021.02.01.004
40. Duca D, Riva G, Pedretti EF, Toscano G (2014) Wood Pellet Quality with respect to EN 14961-2 Standard and Certifications. Fuel 135:9–14. https://doi.org/10.1016/j.fuel.2014.06.042
41. Price-Allison A, Lea-Langton A, Mitchell E, Gudka B, Jones J, Mason P, Williams A (2019) Emissions performance of high moisture wood fuels burned in a residential stove. Fuel, 239: p.1038–1045. https://doi.org/10.1016/j.fuel.2018.11.090
42. Tanko J, Ahmadu U, Sadiq U, Muazu A (2021) Characterization of rice husk and coconut shell briquette as an alternative solid fuel. Adv Energy Convers Mater 1–12. https://doi.org/10.37256/aecm.212021608
43. Sun J, Wang J, Shen Z, Huang Y, Zhang Y, Niu X, Cao J, Zhang Q, Xu H, Zhang N (2019) Volatile Organic Compounds from residential solid fuel burning in Guanzhong Plain, China: source-related profiles and risks. Chemosphere 221:184–192. https://doi.org/10.1016/j.chemosphere.2019.01.002
44. Shen G, Tao S, Chen Y, Zhang Y, Wei S, Xue M, Wang B, Wang R, Lu Y, Li W (2013) Emission characteristics for polycyclic aromatic hydrocarbons from solid fuels burned in domestic stoves in rural China. Environ Sci Technol 47(24):14485–14494. https://doi.org/10.1021/es403110b
45. Sunardi S, Djuanda D, Mandra MAS (2019) Characteristics of charcoal briquettes from agricultural waste with compaction pressure and particle size variation as alternative fuel. Int Energy J 19(3):139–148
46. Da Silva CES, Gomes FJB, Batalha LAR, Lelis RCC, Carvalho AMML, Carneiro AdCO, de Carvalho AM (2021) Recovering wood waste to produce briquettes enriched with commercial kraft lignin. Nat Resour 12(5):181–195. https://doi.org/10.4236/nr.2021.125013
47. Yaseen DF, Taha MAY, Nabi HS, Younis AJ (2020) Study of some wood-charcoal characters produced from some tree species of Duhok Province. J Duhok Univ 23(2):146–152. https://doi.org/10.26682/ajuod.2020.23.2.18
48. Antwi-Boasiako C, Glalah M (2021) Proximate analysis and strength properties of carbonized woods from the most-used tropical timbers from the Afram Plains, Ghana's charcoal production hub. J Sustainable Forestry: p 1–14. https://doi.org/10.1080/10549811.2021.1948869
49. Homdoung N, Uttaruan J, Sasujit K, Wongsiriumnau T, Tippayawong N (2020) Characterization of torrefied biomass pellets from corncobs and rice husks for solid fuel production. Agricultural Engineering International: CIGR Journal, 22(3). http://www.cigrjournal.org
50. Lubwama M, Yiga VA, Lubwama HN (2020) Effects and interactions of the agricultural waste residues and binder type on physical properties and calorific values of carbonized briquettes. Biomass Conversion and Biorefinery: p. 1–21
51. Zhao J, Liu C, Hou T, Lei Z, Yuan T, Shimizu K, Zhang Z (2022) Conversion of biomass waste to solid fuel via hydrothermal co-carbonization of distillers grains and sewage sludge. Bioresour Technol 345:126545. https://doi.org/10.1016/j.biortech.2021.126545
52. Zelinka SL, Altgen M, Emmerich L, Guigo N, Keplinger T, Kymäläinen M, Thybring EE, Thygesen LG (2022) Review of wood modification and wood functionalization technologies. Forests 13(7):1004. https://doi.org/10.3390/f13071004
53. Adamu H, Sabo A, Chinade AA, Lame A (2018) Exploration of influence of chemical composition on combustion and fuel characteristics of wood-charcoals commonly used in Bauchi State, Nigeria. Int Joutnal Renew Energy Res 8(3):1508–1519
54. Atiku F, Mitchell E, Lea-Langton A, Jones J, Williams A, Bartle KD (2016) The impact of fuel properties on the composition of soot produced by the combustion of residential solid fuels in a domestic stove. Fuel Processing Technology, 151: p. 117–125. https://doi.org/10.1016/j.fuproc.2016.05.032
55. He C, Tang C, Li C, Yuan J, Tran K-Q, Bach Q-V, Qiu R, Yang Y (2018) Wet torrefaction of biomass for high quality solid fuel production: a review. Renew Sustain Energy Rev 91:259–271. https://doi.org/10.1016/j.rser.2018.03.097

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.