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Assessment of biomass from an invasive plant, *Eleusine jaegeri*, as a potential feedstock for the production of biomass briquettes

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Abstract
The study assessed the feasibility of *Eleusine jaegeri*, an invasive plant in the Ngorongoro Conservation Area rangelands, as a feedstock for biomass briquette production. It addresses innovative ways of improving rangeland quality while enhancing access to alternative sources of domestic heat energy for the community. The study compared the combustion properties of *E. jaegeri* briquettes with traditional charcoal and rice husk briquettes, including heat energy, volatile matter, ash content, fixed carbon, and moisture content. Additionally, social perceptions were also analyzed in pastoral villages through household surveys and focus group discussions to gauge community acceptance of *E. jaegeri* briquettes as an alternative source of cooking energy. Results showed that *E. jaegeri* biomass exhibited comparable burning qualities to conventional charcoal. The measured contents of heat energy, fixed carbon and moisture from *E. jaegeri* were within the range for various energy applications recommended by the Tanzania Bureau of Standards (TBS). However, its high ash content (41.39%) suggests the need for further refinement in biomass handling and carbonization processes. Community feedback indicated that using *E. jaegeri* briquettes could reduce health risks, improve ecological sustainability, and mitigate human-wildlife conflicts, presenting socio-ecological advantages over traditional fuelwood. Additionally, the efficient burning qualities of biomass briquettes increase user satisfaction, promoting healthier living conditions for rural communities. In conclusion, *E. jaegeri* shows promise as a viable, sustainable bioenergy source, supporting both environmental conservation and economic benefits. Promoting its use as an alternative fuel could positively impact rangeland quality and livelihoods in Tanzania.

Key words: *Biomass briquettes; combustion properties; Eleusine jaegeri; fuel wood; rangelands quality*

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Introduction

In Tanzania, as in many other developing countries, access to sufficient and reliable domestic cooking energy remains a challenge. More than 80% of households still rely on fossil fuels, particularly charcoal and firewood (Doggart *et al*., 2020), whereas the use of clean energy, including natural gas and electricity, accounts for less than 10% (Rupf *et al*., 2015). Notably, long-term reliance on fossil fuels for domestic energy contributes to ongoing greenhouse gas emissions, posing risks to human health, degrading natural landscapes and exacerbating biodiversity loss (Gizachew *et al*., 2020).

The use of biomass briquettes is among the viable long-term solutions to the scarcity of domestic cooking energy (Mwampamba *et al*., 2013). However, in many developing countries, including Tanzania, agricultural and forest wastes are currently the primary feedstocks for briquette production (Sheya and Mushi, 2000). This oversight reflects a broader lack of awareness and exploration of other untapped biomass resources suitable for briquette production.

Biomass from invasive plant species could be utilized as a feedstock for producing briquettes. For example, the wooded shrubs of *Prosopis juliaflora* possess high lignin and cellulose contents. These qualities are ideal for the production of briquettes because their biomass possesses high calorific value and binding properties (Stafford *et al*., 2018). Given that most invasive plant species pose multiple threats to human and natural ecosystems, exploiting them for biomass briquette production offers a double benefit.

The quality of biomass briquettes depends on the types of selected feedstock (Picchio *et al*., 2020). Therefore, end-users should be aware of the various social, economic, and environmental benefits obtained from using briquettes. Through regular training, community understanding and exposure to alternative energy sources like biomass briquettes could be significantly enhanced. This approach can enable them to make informed and wise decisions towards reducing dependency on traditional fossil fuels, particularly fuelwood and charcoal.

Additionally, understanding the thermal properties of briquette feedstocks is crucial before adopting them for various energy applications (Kenney *et al.,* 2013). The calorific value, or heat energy content, is a main indicator of biomass energy potential. Feedstocks with a high calorific value produce more heat energy when burned (Güleç *et al*., 2022). Volatile matter (VM) is part of the feedstock that can be vaporized at a lower temperature and therefore contributes to the quicker ignition of briquettes (Shuk *et al*., 2022). Moisture content (MC) is the portion that represents the amount of water in the feedstock. Briquettes with lower MC burn more efficiently (Róz *et al*., 2015; Zhou *et al*., 2015), and can be transported or stored with the minimum risk of physical damage (Saeed *et al*., 2021).

Furthermore, carbon that remains after the removal of volatile matter (VM) and moisture content (MC) is referred to as fixed carbon (FC). Lastly, the non-combustible mineral matter and impurities inherent in the feedstock are presented by the ash content (AC). Notably, rising AC in feedstock results in a reduction in energy production capacity (Wasfy and Awny, 2020).

The present study aims to assess biomass from an invasive plant, *E. Jaegeri,* as a potential feedstock for the production of biomass briquettes. Within the Ngorongoro Conservation Area (NCA) in Northern Tanzania, *E. jaegeri* is among the dominant invasive plant species across wildlife and pastoral rangelands. The study was conducted to analyse the thermal properties of biomass from *E. jaegeri*. Additionally, to determine the perceptions of the pastoral community within NCA towards the use of briquettes from *E. Jaegeri* as an alternative source of cooking energy.

Exploration of underutilized biomass resources, such as *E. jaegeri* prompts ecologists, sociologists and economists to consider integrating the role of rangeland management with bioenergy production. Such a perspective could establish a diversified and dynamic socio-ecological support system that promotes access to clean cooking energy, safeguards women's welfare, and reduces landscape biodiversity loss.

Materials and methods

Description of study area

The Ngorongoro Conservation Area (NCA), located in the Arusha region of northern Tanzania, is a multiple land use area that is important for both wildlife conservation and livestock grazing by the Maasai pastoralists (Homewood and Rodgers, 1991). The NCA extends from 2°30′-3°30′S to 34°50′-35°55′E, covering an area of 8,292 km². (Figure 1). The annual rainfall ranges from 300 to 630 mm, while the diurnal temperatures range from 7.4 °C to 19.6 °C. Rangelands in NCA are characterized by three major vegetation types: grassland, shrubland and forest (Leweri *et al*., 2021). However, NCA suffers from an increasing population of several invasive plant species, *E. jaegeri* being the dominant one (Figure 2).

Figure 1

A map of the Ngorongoro Conservation Area. Red dots show the study villages.

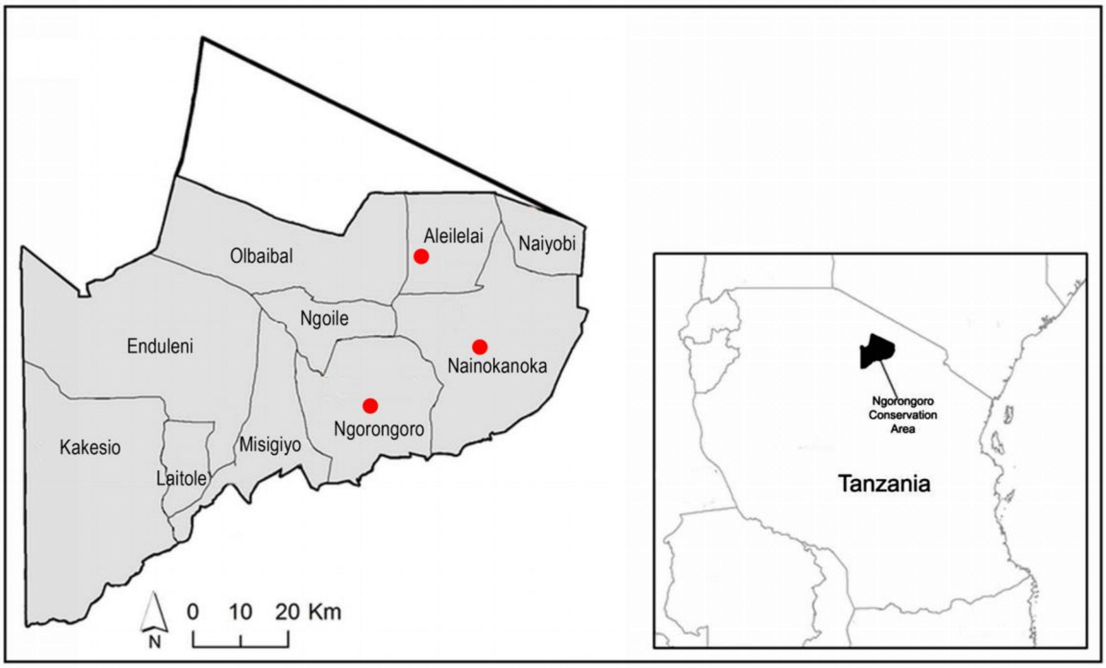

Figure 2

A villager uprooting Eleusine *jaegeri in Ngorongoro Conservation Area rangelands (A). Briquettes produced from E. jaegeri (B). A researcher and villager evaluating the cooking performance of biomass briquettes produced from E. jaegeri (C).*

Study design

All villages in NCA whose rangelands have been colonized by invasive plants were identified. Thereafter, only villages whose rangelands were extensively covered by *E. jaegeri* were isolated. Finally, only three villages were randomly selected as sampling areas.

Samples of biomass from *E. jaegeri were* directly harvested from rangelands in three selected villages, namely Aleililai, Ngorongoro and Nainokanoka (Fig. 1). Samples of rice-husk and conventional charcoal were randomly sourced from local vendors in Karutu town.

Measuring the Thermal Properties of Briquettes

In the lab, replicates of *E. jaegeri*, rice husk and charcoal were placed in separate containers and labeled. Bulk samples were developed, and three replicates of each sample were thoroughly mixed.

Proximate analysis (Van Wychen and Laurens, 2015) was conducted based on the following standards:

ASTM E871-82 (2013) for moisture content; ASTM E1755-01 (2015) for ash content; and ASTM E872-82 (2013) for volatile matter. Fixed carbon was calculated by subtracting the values of moisture, ash and volatile matter content. Details for each procedure are described below:

(i) *Moisture Content (MC)*

A portion of each sample (2 g) was oven-dried at 105 °C for about 120 minutes until it reached a constant weight. The moisture content was calculated using the following equation:

$$MC(\%) = ((W_1 - W_2)/W_1) \times 100 \quad (1)$$

Where: W_1= initial weight, and W_2= weight after drying.

(ii) Volatile Matter (VM)

To determine the volatile matter, 2 g of the sample was heated in a covered crucible at 950 °C for 10 minutes. After cooling, the sample was reweighed. The loss in weight represented the volatile matter content and was calculated as:

$$VM(\%) = ((W_1 - W_2)/W_1) \times 100 \quad (2)$$

Where: W_1 = the original weight of the sample, and W_2 = the weight of the sample after cooling

(iii) Ash Content (AC)
A 2-g sample was placed in a muffle furnace at 600 °C for 60 minutes. After cooling, the ash was weighed, and the ash content was calculated using:

$$AC(\%) = (W2/W1) X 100 \quad (3)$$

Where: W_1 = original weight of dry sample, W_2 = weight of ash after cooling.

(iv) *Calorific Value (CV)*
The calorific value was determined using an oxygen bomb calorimeter (OSK 100 A). The energy content was computed from the observed temperature rise as follows:

$$CV = (E_e + W_1)T_r - C)/S \times 4.1868 \quad (4)$$

Where: E_e is the water equivalent of the calorimeter, W_1 = amount of water in the vessel, T_r = temperature rise, C = correction factor from ignition, and S = weight of the sample (g).

(v) Fixed Carbon (FC)
Fixed carbon was estimated by subtracting the percentages of volatile matter, ash, and moisture content from 100, as shown in the following equation:

$$FC(\%) = 100 - (\%VM + \% C + \% MC) \quad (5)$$

Where: FC(%) is the fixed carbon content of sample, VM = volatile matter content of sample (%), AC = Ash content (%), and MC = Moisture content of sample (%).

Collection of Socio-economic Information
Before conducting interviews, a cooking demonstration was held in each of the three study villages to compare the cooking efficiency of *E. jaegeri* briquettes with that of traditional fuelwood. Villagers from various groups, including elders, youth, women, and community leaders were attended. Two metal pots, each containing 2 kg of goat meat, were then boiled separately on three-stone stoves, one using *E. jaegeri* briquettes and the other using traditional fuelwood as an energy source.

Following each cooking demonstration, focus group discussion (FGD) meetings were conducted. The FGDs aimed to gather insights into community experiences regarding the socio-economic and environmental risks associated with fuel wood use in daily life. They also explored the perceived benefits of biomass briquettes as an alternative cooking fuel within pastoral communities. Each discussion included 20 to 30 participants and lasted between 1 and 2 hours. A checklist of questions was prepared to guide the discussions, ensuring that key topics were systematically covered while allowing flexibility for in-depth responses.

Quantitative data from the proximate analysis of the three samples were summarized as mean, percentage, and range. To quantify community responses during FGD meetings, a Likert scale (Tanujaya *et al.*, 2022) was used to compute summary statistics. Simple descriptive data were presented in tables. All calculations were performed using R software version 2.13 (Crawley, 2012).

Results

Variation in Biomass Thermal Properties
The results of the proximate analysis for the three assessed samples are presented in Table 1. Among the biomass samples, *E. jaegeri* showed a slightly higher moisture content than the other samples. Ash content was notably high across all samples, with rice husk showing the highest level. Volatile matter levels were consistently low, with *E. jaegeri* and rice husk showing particularly low values. Fixed carbon levels varied widely among the samples, with rice husk showing the lowest values and only a slight difference was observed between conventional charcoal and *E. jaegeri*. Heat values showed considerable variation, with *E. jaegeri* exhibiting a value nearly twice that of rice husk, though slightly lower than that of conventional charcoal.

Table 1

Measurements of combustion parameters across different biomass feedstock

Sample	Moisture (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)	Heat value (MJ/kg)
Conventional charcoal	6.39	23.8	23.73	48.08	21.46
E. jaegeri	7.01	41.39	15.92	37.68	16.30
Rice husk	5.98	63.42	17.06	15.54	7.98

Community Perceptions Towards Use of Briquettes from E. jaegeri

The perceived benefits of using briquettes versus fuel wood in terms of socio-economic and ecological impact are presented in Table 2. For socio-economic benefits, briquettes are reported to reduce respiratory infections, save time for women, and reduce injury risks at significantly higher rates than fuel wood. Ecologically, briquettes are also rated more favorably, with notable contributions to restoring native grasses, reducing deforestation, and decreasing wildlife conflicts. Fuelwood shows low positive responses for each category, with minimal ecological benefits.

Table 2

Benefits of using briquettes from E. jaegeri against fuelwood

Benefits		Responses (%)			
		Briquettes		Firewood	
		YES	NO	YES	NO
Socio-economic	Respiratory infections	85	15	20	80
	Save time among women	90	5	20	80
	Reduce risks of injuries	90	10	0	100
Ecological	Restore native grass	90	10	0	100
	Reduce deforestation	100	0	0	100
	Reduce conflict with wildlife	85	15	2	88

Furthermore, briquettes received notably higher positive responses across all properties, indicating greater ease of ignition, less smoke production, higher heat intensity, longer burning time, and reduced ash generation (Table 3). Additionally, there was a strong willingness to use briquettes among respondents, significantly higher than for firewood. In contrast, fuel wood indicated a lower positive response in each category, with the majority of respondents perceived difficulties with ignition, more smoke, lower heat intensity, shorter burning times, more ash, and a lower willingness to use it.

Table 3

Combustion properties of briquettes from E. jaegeri against fuel wood

Property	Responses (%)			
	Briquettes		fuel wood	
	YES	NO	YES	NO
Easy of ignition	85	15	30	70
Less smoke produced	85	15	25	75
High heat intensity	95	5	35	65
Long burning time	84	16	25	75
Less ash generated	65	35	20	80
High willingness to use	85	15	45	55

Discussion

Variations of Combustion Properties of Different Biomass Types

The variation in combustion properties among the three assessed biomass samples has unveiled both proximity and disparities within specific parameters. This variability suggests that briquettes from different feedstocks have potential divergences in their applicability to various energy utilization (Karunanithy *et al.*, 2012).

Although ash content varied substantially among the three samples, it is significantly higher beyond the recommended range. Probably, indicating high accumulation of inorganic matter in biomass caused by poor handling practices (Thy *et al.*, 2013) or due to environmental factors (Goossens *et al.*, 2012). Knowing the actual cause of contamination can help to reduce the risk during the various stages of preparing biomass for briquette production. Notably, harvesting *E. jaegeri* involves the use of a hand hoe (Figure 2). This practice may cause the spontaneous spread of soil particles or dust, contaminating the leaves. However, several inexpensive methods, such as mechanical sieving, can be applied to reduce inorganic impurities in subsequent stages of feedstock processing (Azizan and Jusri, 2021; Thy, *et al.*, 2013). This suggests that local entrepreneurs need training on best practices for handling raw materials to enhance the market acceptability of their briquettes (Falemara *et al.*, 2018).

The observed low moisture content across the three biomass samples suggests that biomass from invasive species, agricultural wastes and common charcoal is suitable for bioenergy production. Biomass with reduced moisture content typically demands less energy to evaporate excess moisture (Obi *et al*., 2020), facilitating efficient combustion and quicker provision of heat energy. The significance of efficiently burning biomass becomes evident during periods such as rainy seasons, when challenges in starting fires can impact daily routines. In Meru County, Kenya, for example, children may attend school without breakfast, and families might skip meals (Waswa *et al*., 2020). Additionally, the ability to generate high and consistent heat energy is crucial for cooking staple African meals, such as maize and beans (Kajumba *et al*., 2022).

Furthermore, the low moisture content of biomass reduces the risk of mold and rot during extended storage (Nyika *et al*., 2024). However, it is crucial to avoid excessively drying biomass, as this can pose some economic disadvantages. This includes increased power bills and accelerated wear of machine parts (Urbano *et al*., 2023).

The observed high volatile matter across all three samples explains their suitability for ease of ignition and high burning efficiency. This quality could be beneficial in communities that often rely on kerosene for ignition purposes. Notably, as the global price of crude oil escalates, kerosene may be unaffordable for many impoverished rural households (Otieno and Awange, 2006).

On the other hand, the variability in volatile matter content among the three samples reveals slight differences in their combustion properties. Although charcoal exhibited the highest volatile matter content, the observed values from *E. jaegeri* and rice husk still fall within an acceptable range for domestic and institutional applications. Cooking regular meals and boiling water often demand a moderate-burning fire (Motghare *et al*., 2016).

The marginal difference in fixed carbon between charcoal and *E. jaegeri* reflects the suitability of biomass from invasive plants for achieving complete combustion. This is a valuable attribute for reducing carbon footprints and other volatile organic compounds associated with cooking and heating (Huang *et al*., 2021). Therefore, biomass from *E. jaegeri* emerges as a promising candidate for producing high-quality briquettes. On the contrary, the low fixed carbon content in rice husks presents various challenges, including inefficient combustion, slow burning, and heightened ash generation. These attributes can affect its acceptance and market viability (Basu, 2018).

However, viable methods exist to enhance the burning efficiency of low-grade biomass, such as that from rice husks. The addition of binding materials, such as starch, contributes to increased cohesion among biomass particles, resulting in denser and more uniform briquettes (Tambunan *et al*., 2023). Increasing compression force during briquette manufacturing leads to heightened density, thereby improving the quality of the resulting briquettes (Mitchual *et al*., 2013). Also, carbonization can enhance structural homogeneity and augment energy density (Basu, 2018).

A notable difference in heat value among the three biomass samples reflects a remarkable difference in their calorific value. Although the measurement from *E. jaegeri* was slightly lower than that from charcoal, its value falls within the accepted range for renewable energy sources recommended by the Tanzania Bureau of Standards for various energy applications (Draft TZS 1312-2019) (TBS, 2022).

Biomasses with high heat energy exhibit complete combustion, which enhances reductions in particulate matter, carbon monoxide, and volatile organic compounds (Ubando *et al*., 2021). Therefore, the use of biomass from *E. jaegeri* can contribute to mitigating of climate change and improving indoor air quality. Later, it benefits the respiratory health of individuals, particularly women and girls, who are the primary users of unclean cooking energy.

Perceived Socio-economic and Environmental Benefits of Using Briquettes from E. jaegeri

The community's feedback on briquettes highlights their advantages in enhancing public health, reducing the environmental footprint, and supporting access to more sustainable energy sources. This suggests that effectively promoting the use of *E. jaegeri* briquettes as an alternative to fuel wood could gain strong acceptance among pastoral communities beyond the NCA, as they offer multiple benefits essential to daily life.

From a social perspective, biomass briquettes were perceived by the community as significantly reducing respiratory infections, with 85% of respondents associating briquettes with a reduction in respiratory issues. This perception aligns with studies that have demonstrated the health risks associated with fuel wood smoke, which contains harmful particulates that increase the risk of respiratory illnesses, particularly among women and children who spend extended periods near cooking fires (WHO, 2018). Cleaner-burning briquettes reduce indoor air pollution by emitting lower levels of harmful particulates, which may potentially lead to a reduction in respiratory infections among users (Martin *et al*., 2013).

Moreover, the time savings associated with briquette use were supported by 90% of respondents, who observed that briquettes could alleviate the significant time burden on women who otherwise collect fuelwood. Studies highlight that fuelwood collection often requires long distances, leaving women with limited time for other productive or educational activities (Mwampamba *et al*., 2013). The transition to biomass briquettes could enable women to allocate more time to socio-economic activities, education, or childcare, thereby contributing to greater gender equality in these communities (Köhlin *et al*., 2011). Furthermore, expanding local access to briquette-making technologies and training on their use could further enhance adoption rates and promote energy independence within the community (Kpalo *et al*., 2020; Mendum and Njenga, 2018).

From an ecological perspective, biomass briquettes offer notable advantages over fuelwood in terms of forest conservation and rangeland quality enhancement. The respondents perceived that the use of briquettes could reduce reliance on trees, thereby directly addressing local deforestation concerns. This perspective is consistent with findings that biomass briquettes sourced from invasive species can help decrease pressure on forest resources by offering an alternative to traditional wood-based fuels (Iiyama *et al.,* 2014). Additionally, the utilization of invasive species such as *E. jaegeri* in briquette production not only conserves native flora but also contributes to the ecological rehabilitation of rangelands. By removing invasive plants, biomass briquette production could potentially improve forage availability, which is essential for maintaining livestock health and promoting biodiversity within these rangelands (Shackleton *et al*., 2019).

Moreover, human-wildlife conflict (HWC) is a persistent issue in many pastoral areas, where forested and densely vegetated landscapes provide cover for predators near livestock grazing zones. In this study, 85% of respondents highlighted that clearing invasive plants for briquette production would reduce vegetation density, which, in turn, could mitigate predator attacks on livestock. This aligns with research indicating that reducing forest cover around livestock areas can decrease ambush opportunities for predators and lower HWC incidences (Nyhus, 2016). Furthermore, the removal of invasive plants from rangelands could help prevent large herbivores from venturing into croplands in search of food, thereby reducing crop depredation (Gray, 2019).

Perceived users' satisfaction with using briquettes from Eleusine jaegeri

In terms of combustion, briquettes outperform fuel wood across all significant properties, contributing to the community's high willingness to adopt them (85%). Briquettes are easier to ignite and produce less smoke, with 85% of respondents noting these properties, compared to only 30% and 25%, respectively, for fuel wood. This ease of ignition and reduced smoke are key advantages that enhance user satisfaction and reduce indoor air pollution (Smith *et al*., 2014). Furthermore, briquettes offer higher heat intensity (95%) and longer burn time (84%) than fuelwood, making them a more efficient and cost-effective cooking option. The ability of briquettes to maintain longer burn times reduces the frequency of refueling, contributing to energy savings for households (Bailis *et al.,* 2015).

The lower ash production of briquettes (65% versus 20% for fuel wood) is another advantage. Reduced ash generation not only simplifies clean-up but also reduces particulate emissions, which are a health hazard in poorly ventilated rural kitchens (Naeher *et al*., 2007). Together, these factors explain the community's greater willingness to use briquettes as a clean, efficient, and health-friendly cooking fuel.

Conclusions and recommendations

The findings from this study underscore the potential of *E. jaegeri* briquettes as a viable and beneficial alternative to traditional fuel wood. The comparative assessment of combustion properties among biomass samples has revealed that *E. jaegeri* briquettes provide effective and efficient energy with low moisture content, high volatile matter, and adequate fixed carbon levels. These attributes make *E. jaegeri* briquettes suitable for domestic and institutional use, particularly in rural pastoral communities. The socio-economic and environmental benefits associated with briquette use, such as reduced respiratory infections, time savings for women, and conservation of forest resources, further support their adoption. Additionally, the ecological advantages, including the mitigation of human-wildlife conflict and the improvement of rangeland quality through the removal of invasive species, contribute positively to biodiversity conservation and livestock health.

The community's favorable perception of *E. jaegeri* briquettes, including their ease of ignition, reduced smoke, high heat intensity, and low ash production, highlights a high level of user satisfaction and willingness to adopt this clean and efficient cooking fuel. Overall, the study suggests that promoting *E. jaegeri* briquettes can enhance both human well-being and ecosystem health, making them a promising solution for sustainable energy in pastoral communities.

To realize these benefits, several recommendations are proposed:

Local entrepreneurs and community members involved in briquette production should receive training on best practices for handling, processing, and storage of raw materials. This will improve briquette quality and increase their acceptability in the market

Supporting the development and access to efficient briquette-making technologies, such as improved extruding machines and dryers, can further enhance their quality and appeal to consumers.

Establishing quality standards, in collaboration with national bodies like the Tanzania Bureau of Standards, can ensure that briquettes meet safety and performance criteria. Certification could increase consumer confidence, attract more buyers, and support the growth of the briquette industry.

To increase adoption rates, it is crucial to raise awareness among rural households about the benefits of briquettes over fuel wood. Community-driven promotion efforts and demonstrations of briquette use in cooking can help change perceptions and encourage more families to switch to this sustainable fuel source.

Policy incentives, such as subsidies or tax reductions for briquette production and distribution, could help reduce initial costs for producers and make briquettes more affordable for consumers. Likewise, encouraging partnerships with local government bodies and NGOs to support briquette adoption in public institutions could create a larger, stable demand for this alternative fuel.

Continued research is recommended to assess long-term community satisfaction and the environmental impacts of *E. jaegeri* briquette use. Studies could focus on monitoring health outcomes related to indoor air quality, economic benefits and broader ecological effects, such as changes in wildlife behavior and vegetation patterns.

By implementing these recommendations, stakeholders can help facilitate a transition towards cleaner, more sustainable energy sources that address both environmental conservation and socio-economic needs.

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Declarations of interest

None.

Authors' contributions

Jerome Kimaro and Isack Legonda designed the study. Material preparation, data collection and analysis were performed by Jerome Kimaro, Victoria Shayo, Hillary Mushi, and Isack Legonda. The first draft of the manuscript was written by Jerome Kimaro, Isack Legonda. All authors commented on previous versions of the manuscript and approved the final manuscript.

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Data availability

The data set associated with the paper should be made available upon request by the Editor-in-chief if the need arises.

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