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Sorghum Biomass as an Alternative Source for Bioenergy

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Abstract: Alternative biomass for energy can reduce fossil fuel use and environmental impacts, providing energy security in semi-arid areas with shallow soils that are not ideal for agro-forestry. The densification of sorghum biomass (SB) brings its energetic characteristics closer those of wood. Higher heating value (HHV) represents the heat produced by a given quantity of fuel. This Brazilian research tested different mixtures of SB, eucalyptus wood (W), and eucalyptus bio-oil (Bo) as briquettes for HHV and least ash. Compressed mixtures of SB+B were compared to W+Bo and SB+W+Bo. The concentrations of bio-oil added to SB/W were 1%, 3%, 4%, and 5%. SB+W+Bo composites' W content was 0%, 25%, 50%, 75%, and 100%, with Bo as 3% of the weight. Sorghum biomass' HHV is equivalent to W at 3%Bo. Bo doses of 4% and 5% had the same HHV as 3%. Eucalyptus wood did not have a significantly greater HHV with any amount of Bo. SB+W+3%Bo had the same HHV as W when W was at least 50% of the mixture. At greater than 36%W, the ash content was lower than 3%, meeting the EN-B international standard. The optimal composite mixture was 64%SB+36%W+3%Bo for HHV and ash content. SB briquettes can be more widely adopted given sorghum's prevalence in semi-arid environments.

Keywords: biomass; bio-oil; energy; eucalyptus; sorghum; wood

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1. Introduction

By 2040, about half of the global energy supply could be from renewable sources [1]. Recent initiatives to increase use of renewable energy have been driven by a desire to reduce greenhouse gas emissions while maintaining economic growth, due to the regional associations of energy consumption from 1975 to 2011 with adverse climatic variables [2]. Using a panel dataset (1980 to 2014) of 35 high-income countries, 40 middle-income countries, and 15 low-income countries, Riti et al. (2017) found that higher per capita GDP was associated with greater greenhouse gas (GHG) emissions, and investments in renewable energy were associated with lower GHG emissions [3]. GHG emissions from the energy systems sector currently make up 34% to 38.8% of total global GHG emissions [4,5] with emissions from biomass currently making up only 0.3% of the total emissions. Globally, fossil fuels power about two-thirds of the production of electricity and heating. About 24.2% of global GHG emissions are from electricity generation and heating which are distributed across four other sectors, namely industrial, agriculture/forestry/other land use, transportation, and buildings [5]. The GHG emissions from biomass used during electricity generation can be divided into one-third of emissions from using natural gas and one-fifth of emissions from using coal [6]. For wood pellets/briquettes, life-cycle GHG emissions are only equivalent to 5% of the emissions from oil [7].

Biomass makes up around 10% [8] to 11% of the global energy mix and is more prevalent in rural areas of the world, where it is used to generate electricity, heat homes, supply process heat for industrial applications [9], and can be converted to biofuels for vehicles [9–11]. Biomass can be used as a direct substitute for fossil fuels and can be burned to produce steam to generate electricity [1]. In addition to direct combustion, electricity can be generated using pyrolysis and gasification; however, these two other techniques are more expensive [6]. By 2025, Indonesia is projected to reach 1857.5 MW or 33.78% of its target of 5500 MW for biomass power plants installed between 2011 and 2019 [12]. Evans et al. (2010) found that Brazil used 7% of global biomass energy for electricity generation [6]. Increasing crop residues and animal manure biomass energy in Rajasthan, India is projected to decrease greenhouse gas emissions relative to those from coal [13].

Despite the potential benefits of lowering the carbon intensity of energy use, biomass fuels are only half as carbon neutral as originally assumed, due to soil carbon depletion [14]. This can result in variable reductions in emissions [15], as seen in Germany with the projected impact on climate change emissions ranging from −5% to 8% (13% range); with woody biomass with forestry being mostly positive, and short-rotation coppices with mixed positive/negative impacts [16]. The net positive emissions for coppices are presumably due to carbon sequestration not being great enough to offset emissions from fossil fuel use during planting, harvesting, etc. Biomass also typically uses more land relative to other energy sources [8] which can compete with food production [15]. Large-scale adoption of biomass by 2050 is projected to increase food prices by 3.2% to 5.2% [17]. Biomass production can also be potentially adversely impacted by climatic changes, via impacts to plant biological pathways [18]. The industrialization of biomass pellets has also been criticized as greenwashing, with questionable environmental and social benefits [19].

In a comprehensive literature review, Abbasi and Abbasi (2010) documented biomass energy sources involving crop residues and wastes over a decade ago, but at that time, crops more exclusively devoted to biomass energy, such as sorghum, were not listed [20]. Sorghum (*Sorghum bicolor* L. Moench) is a very versatile crop since it is widely adaptable due to its C_4 photosynthetic pathway and its high water and nitrogen use efficiencies where genetic improvement has increased biomass, sweetness, and resulted in lower lignin (*bmr*) content [21]. Genetic improvement in sorghum has given it greater biomass productivity and drought tolerance, making it an ideal source of feed, fodder, and biofuel [22]. Sorghum shows promise as an energy crop that can be used for chemical production and heating, in addition to using it in anaerobic digesters to produce biogas [23]. In addition to having high biomass (50 to 80 metric tons per hectare) and potential for ethanol production (1500 to 2800 L per hectare), sorghum also has a short growing period of approximately four months [24]. Sorghum is tolerant to aluminum as well as low levels of phosphorus [25], which makes it suitable for Brazilian soils which in general have low levels of available phosphorus [26].

Future genetic improvement in sorghum can focus on gene editing, advanced omics technologies, and molecular breeding genomic selection [27]. In Minas Gerais state, Brazil, fourteen hybrid, photoperiod-sensitive sorghum cultivars had, on average, better dry mass productivity (34 t ha^{-1}) compared to traditional sorghum cultivars which are typically photoperiod-insensitive [28]. Sorghum biomass can be burned for energy (e.g., heating, electricity generation) and used as a blended additive (5% to 15%) to coal for power plants [29]. Sorghum biomass in Italy had a higher heating value of 19.0 to 19.7 MJ kg^{-1} of dry matter [30]. Sorghum, like other biomass sources, can also be burned in denser forms (e.g., pellets, briquettes) to increase the energy density and thus the efficiency of using biomass as a heating source. Pellets are traditionally made from sawdust and stems without bark from coniferous trees, or can be made from alternative feedstocks which typically have lower bulk density and mechanical durability [31]. Ideally, biomass pellets should be uniform in size, have high bulk and energy density, low moisture content, and be dry, hard, and durable, with low ash content following combustion [32].

ENplus certification is used to indicate pellet quality which can be dependent on the type of biomass used to make pellets, moisture content (recommended 10–15%), size of biomass particles, any binding materials used, as well as pressure and temperature during manufacture. Additives such as maize flour, potato flour, and vegetable oils should not exceed 2% of the total pellet biomass [32]. Although such additives help pellet densification, they decrease the higher heating value. Tumuluru et al. (2018) found that unlike pine, poplar, and maize straw pellets, sorghum pellet density is higher when pellet die diameter size increases from 8 mm to 10 mm. However, sorghum had the lowest pellet density values when compared to pellets made from lodgepole pine, pinyon-juniper, maize stover, and wheat straw [33].

A few studies have compared pellets made from sorghum to wood and other alternative biomass sources. Garcia et al. (2019) used principle component analysis (PCA) and hierarchical clustering agglomerative (HCA) to determine that forest wood biomass (pine, eucalyptus, pine + charcoal) was more favorable compared to non-woody biomass (sugarcane bagasse, bamboo, sorghum, and elephant grass) for pellet production using sorghum from Sete Lagoas in Minas Gerais state in Brazil [34]. In another study, sorghum stalk biomass pellets had the lowest bulk density (365.3 kg m^{-3}) compared to pellets made from maize stover, wheat straw, and big bluestem. Wheat straw pellets had the highest bulk density of 495.8 kg m^{-3}. The moisture content was highest for sorghum stalk biomass pellets (14–16%) compared to maize stover and wheat straw (9–14%) and big bluestem (9–11%) [35].

A meta-analysis of combinations of woody with non-woody biomass found that the pellets conformed to the International Organization for Standardization (ISO) 17,225 standard for pellet diameter and length, contents of moisture, ash, and fine particles, as well as gross calorific value, and bulk density, but not mechanical durability [36]. Ferreira et al. (2019) tested sorghum, sorghum plus 2% wheat starch, and steam-treated sorghum, with plain sorghum being the best for pellet production, having the best bulk and energy densities combined with the least production of fines [37]. The sorghum with wheat starch was the least favorable with the highest moisture content, lowest energy and bulk densities, and the greatest production of fines [37]. All three types met the EN 14961-6 (DIN, 2012) standard for pellets produced from non-wood sources [38]. Sorghum biomass made into briquettes can increase energy density by seven to eight times. Cultivated sorghum test hybrid CMSX S 7016 converted into briquettes at Embrapa Maize and Sorghum in Sete Lagoas, Minas Gerais state, Brazil had similar green biomass as the commercial hybrid BRS 716 [39]. However, pellet boilers may need to be adapted when burning agricultural biomass with sorghum not meeting the NO_x and dust emissions FprEN 303-5 standards in Austria [40].

The goal of this research is to improve the quality of sorghum biomass composites so that sorghum biomass is more comparable to eucalyptus (*Eucalyptus* spp.) wood for energy utilization. While sorghum has future potential as an alternative to maize (*Zea mays*) and sugarcane (*Saccharum officinarum*) for bio-ethanol production [10], we have focused our research on sorghum grown for biomass energy for combustion for industrial applications (e.g., smelting, cement, lime) in semi-arid regions where agro-forestry productivity is limited. Therefore, the objectives of this research were to (1) contextualize the green and dry matter yields of sorghum for biomass energy and to (2) evaluate the higher heating value and lower ash content of briquettes made from eucalyptus wood, sorghum biomass, and eucalyptus/sorghum composites. The percentage by weight of eucalyptus bio-oil added was 1%, 3%, 4%, and 5%, as additives help pellet densification and increase the HHV. Biomass composites evaluated ranged from 0% to 100% sorghum versus eucalyptus wood sawdust combined in increments of 25%.

2. Materials and Methods

2.1. Sorghum, Eucalyptus, and Bio-Oil Production

Sorghum biomass was produced by Embrapa Milho e Sorgo (Corn and Sorghum), in the experimental field located in Sete Lagoas, Minas Gerais state, Brazil. Sorghum biomass was obtained from the sorghum hybrid BRS 716. Sorghum was planted on 1 November 2022 and harvested on 23 March 2023.

The eucalyptus sawdust was collected, with bark, in an area with farmers located in Colombo, Paraná state, Brazil. The eucalyptus bio-oil was produced from eucalyptus by slow pyrolysis with a temperature of 600 °C, a heating rate of 4 °C minute^{-1} and a time retention period of 30 min. The sorghum, eucalyptus wood, and eucalyptus bio-oil were tested for higher heating value, moisture content, and percentage of ash remaining after combustion.

2.2. Biomass Densification into Briquettes

The eucalyptus sawdust from both the tree's wood and bark were compressed in order to make briquettes. To increase the density of the biomass, the moisture content was adjusted to approximately 10%, the densification temperature was 120 °C, with a pressure of ~70 bar. Compressed (i.e., densified) mixtures of alternative biomass—sorghum biomass plus bio-oil—were compared to traditional biomass—eucalyptus (*Eucalyptus* spp.) wood plus bio-oil.

Bio-oil was produced from pyrolysis of eucalyptus. For both sorghum biomass (SB) and eucalyptus wood (W), the concentrations of bio-oil (Bo) added were 1%, 3%, 4%, and 5%. In addition to the SB+Bo and W+Bo mixtures, SB+W+Bo composites ranged from having W constitute 0%, 25%, 50%, 75%, and 100% of the SB+W mixture with all combinations involving the addition of Bo as 3% of the weight of the SB+W (Figure 1).

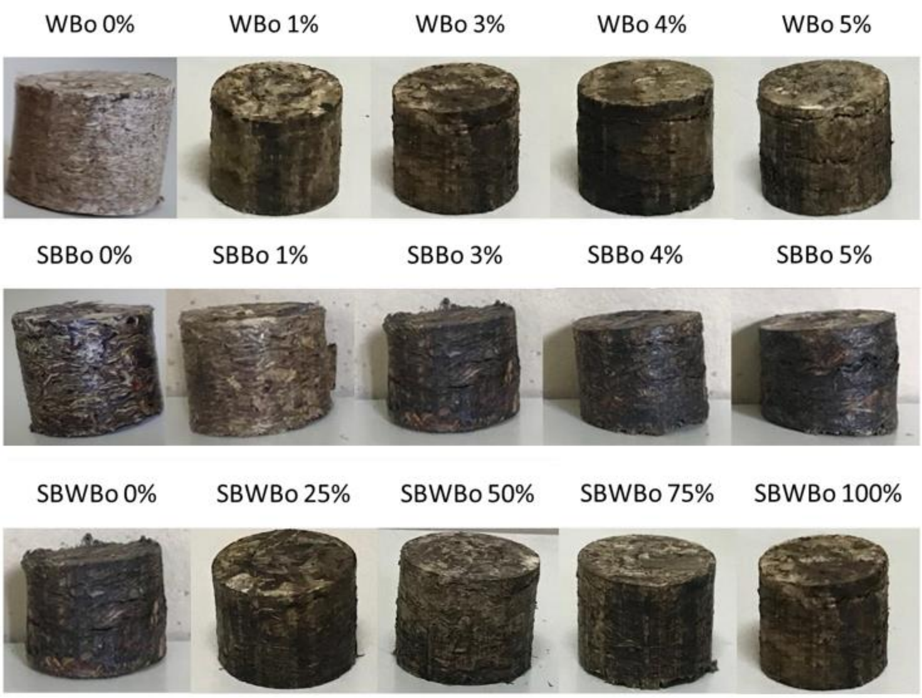

Figure 1. Sorghum biomass (SB) and eucalyptus wood (W) and bio-oil (Bo) composite briquettes.

2.3. Biomass Characterization

The densified biomasses were analyzed for moisture and ash content, as described in the NBR 8112 standard [41]. The higher heating value (HHV) was based on the ASTM

D5865 standard [42]. The sorghum and eucalyptus briquettes' densities were obtained by the ratio between their mass and volume (cylinder):

$$Density = \frac{Mass\ of\ fuel\ (kg)}{Volume\ of\ Fuel\ (m^3)} \tag{1}$$

The energy density (*ED*) of each fuel is calculated using the following equation:

$$ED = HHV \times Density \tag{2}$$

where *HHV* is the higher heating value and *Density* is from Equation (1) above.

The net calorific value was calculated according to equation below [43]:

$$NCV = \left(LHV \times \frac{100 - W}{100} - 6 \times \mathrm{W}\right) \times 0.00419 \tag{3}$$

where NCV = net calorific value (MJ kg^{-1}), LHV = low heat value, (kcal kg^{-1}), W = wet basis moisture content (%), and 0.00419 is the conversion factor from kcal kg^{-1} to MJ kg^{-1}.

The fuel quality index (FQI) was developed according to the methodology from Purohit and Nautiyal (1987) [44]. By using the results of this study, FQI was calculated according to the following equation:

$$FQI = \frac{HHV \times Density}{Ash \times Moisture} \tag{4}$$

where FQI is equal to the HHV (MJ kg^{-1}) times biomass density (kg m^{-3}) which are all divided by the ash content (%) times the moisture content (%).

2.4. Statistical Analyses

To compare briquettes made form only sorghum biomass and only eucalyptus wood sawdust with and without eucalyptus bio-oil and find the better mixture to produce briquettes using different combinations of sorghum, eucalyptus, and bio-oil, a generalized linear model (GLM) was performed using the variables HHV and ash content. This was followed by Tukey post-hoc tests for multiple comparisons at a significance level of 5%. Statistical analyses were performed using Jamovi, from Jamovi Statistics for Windows, Version 2.2 [45].

3. Results

3.1. Biomass Yields

The sorghum biomass used to make the briquettes had a green matter yield of 84.1 metric tons (t) per hectare $(ha)^{-1}$ (Table 1). These yields were similar to historical yields from sorghum biomass grown at Embrapa Agrossilvipastoril in Sinop, Mato Grosso (MT) state, Brazil, from 2013 to 2020. This was during the first crop (i.e., *safra*) planting window from the fall to late winter, which starts with the beginning of the rainy season [46]. Compared to the *safra* planting of sorghum, production during the second crop (i.e., *safrinha*) planting window during the end of the rainy season and start of the dry season has yields that can be about half as much such as sorghum grown in Sinop, MT [46] and Uberlândia, Minas Gerais (MG) [28] (Table 1). These lower yields are not due to drier conditions during *safrinha*, but rather the photoperiod insensitivity of traditional sorghum cultivars. Here, Castro et al. (2015) found that the green matter yields were significantly lower for these traditional varieties (36.96 t ha^{-1}) compared to the sorghum hybrids (56.5 t ha^{-1}) that are photoperiod sensitive [28].

Table 1. Green and dry matter yields of sorghum used to produce briquettes in the current study compared to sorghum biomass yields from the literature.

Country	Study	Year(s)	Location	Planting Date/ Harvest Date	Green Matter Yield (metric tons ha^{-1})	Dry Matter Yield (metric tons ha^{-1})
Brazil	Current	2022–2023	Sete Lagoas, Minas Gerais	1 November to 23 March [1]	84.1	30.6
	Morales et al., 2023 [46]	2013–2020	Sinop, Mato Grosso	Various [1]	89.5	34.5
		2014, 2019	Sinop, MT	Various [2]	56.2	20.5
	Castro et al., 2015 [28] *	2013–2014	Lavras, MG	29 November to 20 May [1]	88.9	-
		2013–2014	Sete Lagoas, MG	21 November to 11 March [1]	41.6	-
		2014	Uberlândia, MG	13 March to 26 June [2]	39.0	-
	Perazzo et al., 2014 [47]	2011	Soledade, Paraíba	5 March to 28 May/7 June [2]	55.0	14.9
Italy	Pannacci and Bartolini 2018 [30]	2005	Perugia, Umbria	17 May to 13 October	66.5	21.0
		2006	Perugia, Umbria	15 May to 25 September	63.7	29.2

[1] Typically the first crop (*safra*) was grown from November to February in Brazil. [2] Typically the second crop (*safrinha*) was grown from March to June in Brazil. * This study excluded genotypes Volumax and BR655 which are forage sorghums.

Fertilizing sorghum can increase crop yields. While the green matter and dry matter yields presented in Table 1 from research in Italy are averaged across nitrogen (N) fertilization levels of 0, 50, 100, and 150 kg ha^{-1}, Pannacci and Bartolini (2018) found optimal nitrogen (N) fertilization at 100 kg ha^{-1} of N, resulting in sorghum biomass dry matter (DM) that was 23.8% higher in 2005 and 18.8% higher in 2006. The baseline unfertilized sorghum biomass yields were 18.5 t ha^{-1} of DM in 2005 and 26.6 t ha^{-1} in 2006 [30].

Even with adequate fertilization and crop management of this drought-tolerant crop, sorghum green matter and dry matter yields can still be impacted by dry climates and weather conditions during any given growing season. For example, there were lower yields for both green matter (55.0 t ha^{-1}) and dry matter (14.9 t ha^{-1}) for sorghum in the drier Caatinga biome in Soledade, Paraíba compared to other biomes in Brazil, such as the Atlantic Forest (both Lavras and Sete Lagoas in Minas Gerais) and the Amazon (Sinop, Mato Grosso) transition zone (Table 1). Even though 2013–2014 was the start of an abnormally dry five years in many areas of Brazil [48], localized variations in green matter yields in Minas Gerais state were apparent with only 41.6 t ha^{-1} in Sete Lagoas compared to 88.9 t ha^{-1} in Lavras. However, sorghum in Lavras was not harvested for another two months after sorghum was harvested in Sete Lagoas (Table 1).

3.2. Energy Properties of Biomass and Bio-Oil

Long-lasting embers can produce uniform heat, which is more effective for space heating and industrial burning processes. Therefore, densification is required in order to burn sorghum biomass as a fuel. The higher heating value, moisture, ash contents, fixed carbon, and net calorific value of the components used to make briquettes are summarized in Table 2. The net calorific value considered the biomass wet basis moisture content (biofuel moisture as received). It is an important measurement for a moist fuel, since the HHV decreases (e.g., raw products, Table 2) because a portion of the combustion heat is used up to evaporate moisture (endotherm phase) in the biomass. This evaporated moisture does not return the heat back to the system. Furthermore, higher proportions of water not only decrease energy delivery, but also reduce furnace temperature and increase the amount of condensable gas released (volatile materials), composed of tars and acidic water vapors that can be deposited on furnace walls, causing obstructions, in addition to reducing service life due to acid corrosion [49]. Therefore, the moisture content is an important parameter to be considered in a biofuel.

Table 2. Component properties of sorghum biomass and eucalyptus wood and bio-oil used to make biomass briquettes.

Biomass Processing	Biomass Type	Higher Heating Value (MJ kg^{-1})	Moisture Content (%)	Net Calorific Value (MJ kg^{-1})	Ash Content (%)	Fixed Carbon (%)
Raw product	Eucalyptus sawdust [1]	18.8	60	4.9	3.9	21.2
	Sorghum biomass	18.0	55	5.4	3.9	16.3
Compressed	Sorghum biomass	18.0	7.5	13.8	3.9	16.3
	Eucalyptus sawdust [1]	18.8	5.7	15.2	1.3	21.2
Bio-oil (pyrolysis)	Eucalyptus	29.8	30	14.0	0.04	17.3

[1] Includes bark of eucalyptus.

According to the standards of pellet quality ISO 17225-2, ISO 17225-6 [50,51], and EN14961-2 [50], the net calorific value for industrial use should be greater than or equal to 14.5 MJ kg^{-1}. The higher heating value (HHV) of eucalyptus sawdust (WBo0%) and sorghum biomass (SBBo0%) are outstanding, with values equal to 18.8 MJ kg^{-1} and 18.0 MJ kg^{-1}, respectively. As expected, WBo0% has a higher HHV (p_{Tukey} = 0.01) when compared to sorghum biomass. This is related to both the high volatile matter (WBo0% = 82.4, SD = 0.3; SBBo0% = 74.8, SD = 0.8) and low ash content (WBo0% = 1.3; SD = 0.07; SBBo0% = 3.9, SD = 0.11), as shown in Figure 2. It is important to remember that the ash does not participate in the energy generation process, since it is only a residue from the combustion process. However, the ash is accounted for in the calculation of fixed carbon, that is, the mass of fuel subjected to combustion [52].

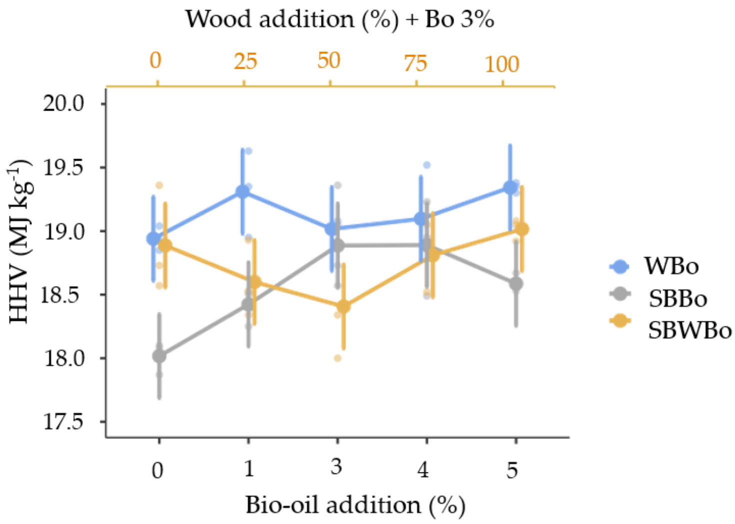

Figure 2. Higher heating value (HHV; MJ kg^{-1}) for densified mixtures of sorghum biomass plus bio-oil (SBBo), eucalyptus sawdust and bio-oil (WBo), and sorghum, wood, and bio-oil (SBWBo3%). The circles are the higher heating value (HHV) means, the bars are the confidence interval of the mean (p_{Tukey} < 0.05), and the blue, orange, and gray dots are the HHV repetitions measured for each treatment.

The addition of bio-oil (Bo) did not increase the higher heating value (HHV) of eucalyptus wood (p_{Tukey} > 0.05). However, the addition of 3% Bo increased the HHV for sorghum biomass, producing the same amount of energy as eucalyptus wood (p_{Tukey} < 0.004), as shown in Figure 2. In another words, alternative biomass can produce the same amount of energy compared to traditional biomass by adding 3% of Bo. Also, the addition of 5% bio-oil for both sorghum biomass (SB) and eucalyptus wood (W) presented physical bio-oil (Bo) losses during the compression process. The same did not happen with the addition of 3% and 4% Bo. Including W in the SBWBo3% mixture resulted in the same energy content for all doses, demonstrating the capability of Bo to increase the HHV, since Bo has a HHV equal to 30.7 MJ kg^{-1}.

Given the importance of diversifying sources for energy production, both SB and W types of biomass with or without the addition of Bo could be used for industrial purposes such as heating and generating electricity to complement existing non-renewable sources. However, in spite of the promising HHV reported, the type of Bo that was used in this research should not be used for domestic purposes such as cooking where the smoke from burning the Bo would come into contact with food. Bo contains toxic compounds, namely polycyclic aromatic hydrocarbons [53].

The standard ISO 17225-2 [50] related to solid biofuel graded wood pellets established a restrictive ash content less than or equal to 0.7% by weight for optimal pellet quality, which is classified as either ENplus-A1 or ENplus-A2 [38]. Lower quality pellets generate ash that is greater than 0.7% to 3.0% by weight and is classified as EN-B [38]. It is widely known that ash does not provide energy value to fuel because ash is composed of inorganic elements that lead to several drawbacks during combustion. High ash content accelerates furnace wear via encrusting and corrosion. This can increase the cost of burning due to added cleaning and ash disposal [54].

The bio-oil (Bo) addition did not alter the ash content of sorghum biomass nor that of the eucalyptus wood ($p_{Tukey} < 0.05$), as indicated in Figure 3. The average ash content for sorghum biomass (SB) is 3.9% by weight and for eucalyptus wood it is 1.3% by weight. The standard ISO 17225-2 related to solid biofuel graded wood pellets established that the ash content of pellets must be less than or equal to 3.0% by weight for industrial use [50]. Adding SB up to 64% of the composite mixture can guarantee this standard of quality (Figure 3).

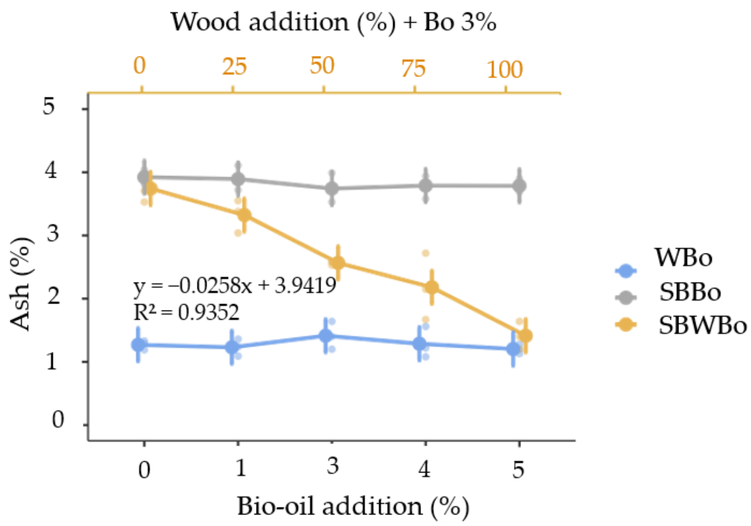

Figure 3. Ash content (%) of densified mixtures of sorghum biomass plus bio-oil (SBBo), eucalyptus sawdust and bio-oil (WBo), and sorghum, wood, and bio-oil (SBWBo3%). The circles are the higher heating value (HHV) means, the bars are the confidence interval of the mean ($p_{Tukey} < 0.05$), and the blue, orange, and gray dots are the HHV repetitions measured for each treatment.

The quality of biomass fuel is important. Low moisture, lower ash content, and a greater ability to produce hot and durable flame are the quality criterion used to rank the preferred biomass for energy. Clearly, eucalyptus wood (W) with 0% Bo has a better fuel quality index compared to treatments containing SB (Figure 4).

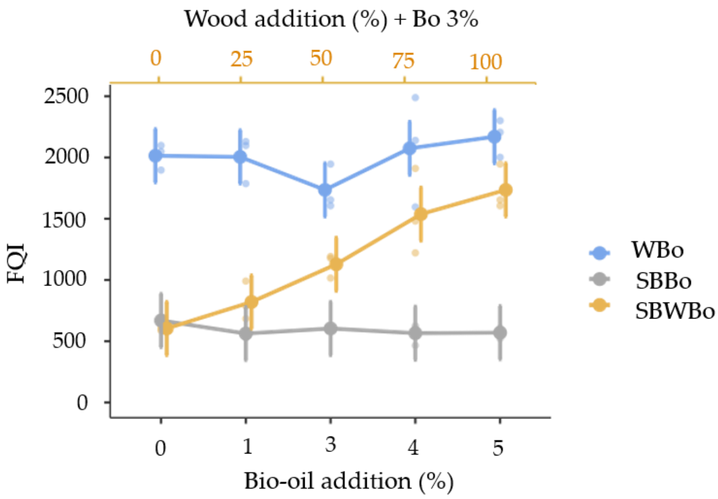

Figure 4. Fuel quality index of densified mixtures of sorghum biomass plus bio-oil (SBBo); eucalyptus sawdust and bio-oil (WBo); and sorghum, wood, and bio-oil (SBWBo3%). The circles are the higher heating value (HHV) means, the bars are the confidence interval of the mean ($p_{Tukey} < 0.05$), and the blue, orange, and gray dots are the HHV repetitions measured for each treatment.

While W has the same density and the same moisture content as SB composites due to the compression process, W has a higher heating value and lower ash content. The composite made with 64% SB, 36% W, plus 3% Bo is ideal, since it has the same heating value as W with a low ash content of 3%; its density is also unchanged (Figure 5) and it meets the EN-B standard [51]. The circles are the higher heating value (HHV) means, the bars are the confidence interval of the mean ($p_{Tukey} < 0.05$), and the blue dots are the HHV measured for each repetition.

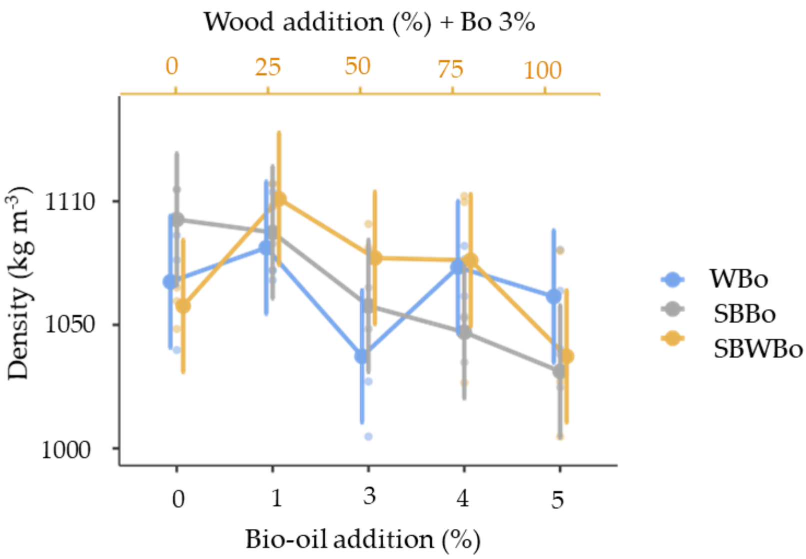

Figure 5. Density of densified mixtures of sorghum biomass plus bio-oil (SBBo), eucalyptus sawdust and bio-oil (WBo), and sorghum, wood, and bio-oil (SBWBo3%). The circles are the higher heating value (HHV) means, the bars are the confidence interval of the mean ($p_{Tukey} < 0.05$), and the blue, orange, and gray dots are the HHV repetitions measured for each treatment.

4. Discussion

4.1. Comparing Results to Past Research

The higher heating values in our study for compressed sorghum biomass (18.0 MJ kg^{-1}; Table 2) were similar to past sorghum studies in the literature. For example, in Minas Gerais state in Brazil, Castro et al. (2015) found the higher heating value (HHV) for sorghum was 4411.37 kcal kg^{-1} which equals 18.47 MJ kg^{-1}, which was greater than other biomass sources such as maize stalk, sugarcane bagasse, bean stalk, and sawdust, while being slightly lower than coffee silver skin and soybean stalk [28]. In São Paulo state, Brazil, Garcia et al. (2019) measured the HHV for sorghum (19.34 MJ kg^{-1} +/−0.22) in addition to other biomass energy sources such as sugarcane bagasse (18.52 MJ kg^{-1} +/−0.18), elephant grass (18.51 MJ kg^{-1} +/−0.26), bamboo (19.64 MJ kg^{-1} +/−0.16), eucalyptus (19.76 MJ kg^{-1} +/−0.72), pine + charcoal mixtures (5% to 15%) ranging from 20.42 MJ kg^{-1} +/−0.14 for the 5% mixture to 20.95 MJ kg^{-1} +/−0.47 for the 15% mixture, and pine (20.65 MJ kg^{-1} +/−0.46) [34]. The sorghum HHV in Italy ranged from 17.6 MJ kg^{-1} for unfertilized sorghum to 19.7 MJ kg^{-1} for sorghum fertilized with 100 kg ha^{-1} of nitrogen [30].

For eucalyptus wood, the HHV from our study for both raw and compressed was 18.8 MJ kg^{-1}. Eucalyptus sawdust in São Paulo state, Brazil, from the forest wood biomass types evaluated, had a HHV of 20.71 MJ kg^{-1}. In this past research study in São Paulo state, Garcia et al. (2019) also found that forest wood (e.g., pine, eucalyptus) biomasses were more favorable than non-woody biomass types such as sorghum due to higher average energy density for wood (13.95 GJ m^{-3}) compared to alternative biomass pellets [34]. This wood energy density was 16.32 GJ m^{-3} for eucalyptus sawdust (Table 2). The energy density of sorghum in our study was 15.07 GJ m^{-3}, as shown in Table 2. Garcia et al. (2019) measured energy density for sorghum at 11.75 GJ m^{-3} +/−0.22, which was lower compared to pine + charcoal mixtures (13.63 GJ m^{-3} +/−0.24 for the 5% mixture to 14.23 GJ m^{-3} +/−0.23 for the 15% mixture), bamboo (14.26 GJ m^{-3} +/−0.16), pine (14.24 GJ m^{-3} +/−0.19), and eucalyptus (14.01 GJ m^{-3} +/−0.08), but higher than sugarcane bagasse (10.74 GJ m^{-3} +/−0.15) and elephant grass (9.43 GJ m^{-3} +/−0.15) [34].

4.2. Agro-Forestry Alternative for Energy and Other Uses

Despite the land-extensive nature of growing annual or perennial crops for energy [8] and the potential for direct competition with producing crops for food [15], some regions of the world, such as northeast Brazil, have dry climates that are not conducive for agro-forestry and wood-based bioenergy. In these regions, annual crops such as sorghum are being grown for energy purposes [47]. Compared to eucalyptus biomass after 5 years of establishment (20 t ha^{-1} yr^{-1} of dry matter) [55], sorghum can produce 50% more dry matter if grown as a first crop and can be competitive with eucalyptus as a second crop without having to wait years for maturity (Table 1). It may be possible for sorghum to have double the dry matter yield (40 t ha^{-1} of dry matter) compared to eucalyptus [55]. Using the higher heating value for sorghum measured in this study at 18 MJ kg^{-1} $\times$ 1000 kg metric ton $(t)^{-1}$ = 18,000 MJ t^{-1}, and multiplying this with an assumed average dry matter yield of 20 t ha^{-1} results in 18,000 MJ t^{-1} $\times$ 20 t ha^{-1} = 360,000 MJ ha^{-1} = 0.36 TJ ha^{-1} for sorghum.

There are many potential applications for more widely adopting sorghum for energy. Sorghum cultivars are specialized in energy utilization but also can be dual-purpose [56]. Dual-purpose (e.g., feed, biomass) sorghum cultivars allow a second harvest of tiller regrowth after the first cut [47,55]. However, the green matter yield of this second cut is only one-tenth to one-fifth of the first cut [55]. While sorghum is widely grown as an animal feed in Brazil, other regions of the world rely on sorghum as a staple grain which is typically grown at small-scale [57]. Sorghum can also be added as an alternative annual cropping option to diversify annual crop sequences in integrated crop–livestock–forestry systems in Brazil that currently do not use sorghum [58–60].

4.3. Sustainability Implications of Sorghum Biomass

We have demonstrated that sorghum briquettes can be produced that are comparable to eucalyptus wood. This adds another utilization option for this crop beyond historical uses for feed, forage, bio-ethanol, and brooms. Past research suggests that utilizing sorghum as an alternative energy source can be profitable if the cost of producing biomass briquettes or pellets can be kept under USD 120 per metric ton, which is dependent on the cost of raw materials [61]. From an economic profitability perspective, it is important to have a high biomass density or yield of energy per hectare since transportation costs can reduce profitability [6]. In addition to economics, the environmental and social considerations of sorghum biomass production and use for energy need to be further explored. The sustainability of biomass energy involves (1) economic considerations of resource availability, cost, and efficiency; (2) environmental impacts such as greenhouse gas emissions, water use, and land use; (3) social impacts such as competition with food production and increased work opportunities from higher labor demand required for biomass energy generation; as well as (4) ecological impacts on wildlife due to land use conversion from native habitats to intensive agriculture [6].

5. Conclusions

Alternative sources of biomass energy are necessary to diversify options for agricultural producers and industrial purposes, especially in areas where wood is not available or cannot grow. Densification for briquettes is necessary for a better use of alternative sources of biomass with low density, such as sorghum biomass, considering logistics, storage, and industrial automatization. Densification with 3% of bio-oil added can make sorghum biomass competitive with wood in terms of higher heating value content. Also, with eucalyptus sawdust added, accounting for more than 36% of the composite briquette, the ash content was lower than 3%, which meets the EN-B international standard. When considering both the higher heating value and ash content, the optimal composite mixture was 64% sorghum biomass, 36% eucalyptus sawdust, and 3% bio-oil. This type of briquette can be adopted with the same quality as wood.

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References

1. Alidrisi, H.; Demirbas, A. Enhanced electricity generation using biomass materials. *Energy Sources Part A Recovery Util. Environ. Eff.* **2016**, *38*, 1419–1427. [CrossRef]
2. Akhmat, G.; Zaman, K.; Shukui, T.; Sajjad, F. Does energy consumption contribute to climate change? Evidence from major regions of the world. *Renew. Sustain. Energy Rev.* **2014**, *36*, 123–134. [CrossRef]
3. Riti, J.S.; Shu, Y.; Song, D.; Kamah, M. The contribution of energy use and financial development by source in climate change mitigation process: A global empirical perspective. *J. Clean. Prod.* **2017**, *148*, 882–894. [CrossRef]

4. Yoro, K.O.; Daramola, M.O. Chapter 1-CO_2 emission sources, greenhouse gases, and the global warming effect. In *Advances in Carbon Capture: Methods, Technologies and Applications*, 1st ed.; Rahimpour, M.R., Farsi, M., Makarem, M.A., Eds.; Elsevier Science: Amsterdam, The Netherlands, 2020; pp. 3–28 (570 pp.). ISBN 0128196572. [CrossRef]
5. Lamb, W.F.; Wiedmann, T.; Pongratz, J.; Andrew, R.; Crippa, M.; Olivier, J.G.J.; Wiedenhofer, D.; Mattioli, G.; Khourdajie, A.A.; House, J.; et al. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environ. Res. Lett.* **2021**, *16*, 073005. [CrossRef]
6. Evans, A.; Strezov, V.; Evans, T.J. Sustainability considerations for electricity generation from biomass. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1419–1427. [CrossRef]
7. Raymer, A.K.P. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass Bioenergy* **2006**, *30*, 605–617. [CrossRef]
8. Timmons, D.; Harris, J.M.; Roach, B. *The Economics of Renewable Energy*; An ECI Teaching Module on Social and Environmental Issues in Economics; Global Development Policy Center, Boston University: Boston, MA, USA, 2024. Available online: https://www.bu.edu/eci/files/2024/03/renewable-energy-econ-module-final.pdf (accessed on 4 June 2024).
9. Kaygusuz, K. Climate Change and Biomass Energy for Sustainability. *Energy Sources Part B Econ. Plan. Policy* **2010**, *5*, 133–146. [CrossRef]
10. Frankowski, J.; Wawro, A.; Batog, J.; Szambelan, K.; Łacka, A. Bioethanol Production Efficiency from Sorghum Waste Biomass. *Energies* **2022**, *15*, 3132. [CrossRef]
11. Srivastav, A.L.; Bhardwaj, A.K.; Kumar, M. (Eds.) *Valorization of Biomass Wastes for Environmental Sustainability: Green Practices for the Rural Circular Economy*, 1st ed.; Springer: Cham, Switzerland, 2024; pp. 1–337. ISBN 978-3-031-52484-4/978-3-031-52485-1. [CrossRef]
12. Primadita, D.S.; Kumara, I.N.S.; Ariastina, W.G. A Review on Biomass for Electricity Generation in Indonesia. *J. Electr. Electron. Inform.* **2020**, *4*, 1–9. [CrossRef]
13. Vijay, V.; Kapoor, R.; Singh, P.; Hiloidhari, M.; Ghosh, P. Sustainable utilization of biomass resources for decentralized energy generation and climate change mitigation: A regional case study in India. *Environ. Res.* **2022**, *212 Pt B*, 113257. [CrossRef]
14. Ahamer, G. How to Compute Whether Biomass Fuels Are Carbon Neutral. *C* **2024**, *10*, 48. [CrossRef]
15. Azar, C. Biomass for energy: A dream come true. . .or a nightmare? *Wiley Interdiscip. Rev. Clim. Chang.* **2011**, *2*, 309–323. [CrossRef]
16. Gutsch, M.; Lasch-Born, P.; Lüttger, A.B.; Suckow, F.; Murawski, A.; Pilz, T. Uncertainty of biomass contributions from agriculture and forestry to renewable energy resources under climate change. *Meteorol. Z.* **2015**, *24*, 213–223. [CrossRef]
17. Winchester, N.; Reilly, J.M. The feasibility, costs, and environmental implications of large-scale biomass energy. *Energy Econ.* **2015**, *51*, 188–203. [CrossRef]
18. De Freitas, E.N.; Salgado, J.C.S.; Alnoch, R.C.; Contato, A.G.; Habermann, E.; Michelin, M.; Martinez, C.A.; Polizeli, M.d.L.T.M. Challenges of Biomass Utilization for Bioenergy in a Climate Change Scenario. *Biology* **2021**, *10*, 1277. [CrossRef]
19. Kinefuchi, E. Burning forests: The wood pellet industry's framing of sustainability and its shadow places. *Front. Commun.* **2024**, *9*, 1237141. [CrossRef]
20. Abbasi, T.; Abbasi, S.A. Biomass energy and the environmental impacts associated with its production and utilization. *Renew. Sustain. Energy Rev.* **2010**, *14*, 919–937. [CrossRef]
21. Prakasham, R.S.; Nagaiah, D.; Vinutha, K.S.; Uma, A.; Chiranjeevi, T.; Umakanth, A.V.; Rao, P.S.; Yan, N. Sorghum biomass: A novel renewable carbon source for industrial bioproducts. *Biofuels* **2014**, *5*, 159–174. [CrossRef]
22. Ahmad, T.; Buneen, U.; Sajid, S.N.; Almas, H.I.; Haseeb, A.; Rubab, A.; Kanwal, M.; Arsh, Q.E.; Asghar, H. Morphological and molecular diversity analyses of high biomass sorghum (*Sorghum bicolor* L. Moench). *Int. J. Biosci.* **2020**, *16*, 253–273, ISSN 2220-665 (Print), 2222-5234 (Online).
23. Staggenborg, S. Forage and Renewable Sorghum End Uses. In *Sorghum: A State of the Art and Future Perspectives*; Ciampitti, I.A., Prasad, P.V., Eds.; American Society of Agronomy Crop Science Society of America Soil Science Society of America: Madison, WI, USA, 2019; Volume 58, Chapter 20; pp. 441–461. [CrossRef]
24. Umakanth, A.V.; Paroha, S.; Kumar, A.; Ranganathan, A.; Swain, D. Sweet Sorghum for Biofuel Production in Sub-Tropical India. *J. Sci. Res. Rep.* **2024**, *30*, 1–9. [CrossRef]
25. Da Costa Parrella, R.A.; Schaffert, R.E.; de Menezes, C.B.; Rodrigues, J.A.S.; Magalhães, J.V.; Damasceno, C.M.B.; da Silva, D.D.; Mendes, S.M. Improving sorghum cultivation in South America. In *Achieving Sustainable Cultivation of Sorghum Volume 2*, 1st ed.; Rooney, B., Ed.; Burleigh Dodds Science Publishing: Cambridge, UK, 2017; Chapter 7; 34p, ISBN 9781351114394. [CrossRef]
26. Pavinato, P.S.; Cherubin, M.R.; Soltangheisi, A.; Rocha, G.C.; Chadwick, D.R.; Jones, D.L. Revealing soil legacy phosphorus to promote sustainable agriculture in Brazil. *Sci. Rep.* **2020**, *10*, 15615. [CrossRef] [PubMed]
27. Yang, L.; Zhou, Q.; Sheng, X.; Chen, X.; Hua, Y.; Lin, S.; Luo, Q.; Yu, B.; Shao, T.; Wu, Y.; et al. Harnessing the Genetic Basis of Sorghum Biomass-Related Traits to Facilitate Bioenergy Applications. *Int. J. Mol. Sci.* **2023**, *24*, 14549. [CrossRef] [PubMed]
28. Castro, F.M.R.; Bruzi, A.T.; Nunes, J.A.R.; Parrella, R.A.C.; Lombardi, G.M.R.; Albuquerque, C.J.B.; Lopes, M. Agronomic and Energetic Potential of Biomass Sorghum Genotypes. *Am. J. Plant Sci.* **2015**, *6*, 1862–1873. [CrossRef]
29. Suyatno, H.; Prayoga, M.Z.E.; Sugiyono, A.; Maulana, I.; Ruhiyat, A.S.; Hidayat, Y. Investigation on Potential of Slagging Fouling and Corrosion in Co-firing Bituminous Coal and Sorghum Waste Pellet. *Int. J. Appl. Sci. Technol. Eng.* **2023**, *1*, 197–203, ISSN 2987-2499. [CrossRef]

30. Pannacci, E.; Bartolini, S. Effect of nitrogen fertilization on sorghum for biomass production. *Agron. Res.* **2018**, *16*, 2146–2155. [CrossRef]
31. Picchio, R.; Di Marzio, N.; Cozzolino, L.; Venanzi, R.; Stefanoni, W.; Bianchini, L.; Pari, L.; Latterini, F. Pellet Production from Pruning and Alternative Forest Biomass: A Review of the Most Recent Research Findings. *Materials* **2023**, *16*, 4689. [CrossRef] [PubMed]
32. Kwapong, N.A. Biomass Pelletisation: Influence of Biomass Characteristics on Pellet Quality. Technical Article, Biomass Connect. March 2023. Available online: https://www.biomassconnect.org/technical-articles/biomass-pelletisation-influence-of-biomass-characteristics-on-pellet-quality/ (accessed on 28 May 2024).
33. Tumuluru, J.S. Effect of pellet die diameter on density and durability of pellets made from high moisture woody and herbaceous biomass. *Carbon Resour. Convers.* **2018**, *1*, 44–54. [CrossRef]
34. Garcia, D.P.; Caraschi, J.C.; Ventorim, G.; Vieira, F.H.A.; de Paula Protásio, T. Assessment of plant biomass for pellet production using multivariate statistics (PCA and HCA). *Renew. Energy* **2019**, *139*, 796–805. [CrossRef]
35. Theerarattananoon, K.; Xu, F.; Wilson, J.; Ballard, R.; Mckinney, L.; Staggenborg, S.; Vadlani, P.; Pei, Z.J.; Wang, D. Physical properties of pellets made from sorghum stalk, corn stover, wheat straw, and big bluestem. *Ind. Crops Prod.* **2011**, *33*, 325–332. [CrossRef]
36. Rupasinghe, R.L.; Perera, P.; Bandara, R.; Amarasekera, H.; Vlosky, R. Insights into Properties of Biomass Energy Pellets Made from Mixtures of Woody and Non-Woody Biomass: A Meta-Analysis. *Energies* **2024**, *17*, 54. [CrossRef]
37. Ferreira, I.R.; dos Santos, R.; Castro, R.; de Cássia Oliveira Carneiro, A.; Castro, A.F.; de Sousa Santos, C.P.; de Lima Costa, S.E.; Mairinck, K. Sorghum (*Sorghum biocolor*) Pellet Production and Characterization. *Floresta e Ambient.* **2019**, *26*, e20171001. [CrossRef]
38. *NBR 8112: EN 14961-2:2012 & EN 14961-2:2011*; Solid Biofuels: Fuel Specification and Classes. Part 2: Wood Pellets for Non-Industrial Use. European Committee for Standardization (CEN): Brussels, Belgium, 2011. Available online: https://standards.globalspec.com/std/1381909/en-14961-2 (accessed on 28 May 2024).
39. Tannús, C.M.; Santos, A.C.; Pereira, G.S.J.; Alves, M.G.; Corrêa, L.V.T.; da Costa Parrella, R.; Sette, C.R. Technical Feasibility of Sorghum Biomass for Briquettes Production. *TreeDimensional J.* **2023**, *1*, e2023023. [CrossRef]
40. Carvalho, L.; Wopienka, E.; Pointner, C.; Lundgren, J.; Verma, V.K.; Haslinger, W.; Schmidl, C. Performance of a pellet boiler fired with agricultural fuels. *Appl. Energy* **2013**, *104*, 286–296. [CrossRef]
41. *NBR 8112*; Carvão Vegetal: Análise Imediata. Associação Brasileira de Normas Técnicas (ABNT): Rio de Janeiro, Brazil, 1986. Available online: https://www.normas.com.br/visualizar/abnt-nbr-nm/3314/abnt-nbr8112-carvao-vegetal-analise-imediata (accessed on 28 May 2024).
42. *D5868 2013*; Standard Test Method for Gross Calorific Value of Coal and Coke. American Society for Testing and Material (ASTM): West Conshohocken, PA, USA, 2013. Available online: https://standards.globalspec.com/std/3852823/astm-d5865-13 (accessed on 28 May 2024).
43. Brito, J.O. Expressão da produção florestal em unidades energéticas. In *Congresso Florestal Panamericano, Congresso Forestal Brazileiro, Curitiba, Floresta para o Desenvolvimento: Política, Ambiente, Tecnologia e Mercado*; SBS, SBEF: Anais, São Paulo, Brazil, 1993; Volume 3, pp. 280–282. Available online: https://repositorio.usp.br/item/000859490 (accessed on 6 August 2024).
44. Purohit, A.N.; Nautiyal, A.R. Fuelwood Value Index of Indian mountain tree species. *Int. Tree Crops J.* **1987**, *4*, 177–182. [CrossRef]
45. Jamovi. Open Statistical Software for the Desktop and Cloud. 2023. Available online: https://www.jamovi.org/ (accessed on 6 July 2023).
46. Morales, M.M.; Tardin, F.D.; Behling, M.; de Abreu, D.C.; Martins, A.R.R.; André, V.L.S.; Porto, F.L. Eucalipto e sorgo biomassa para geração de energia em Mato Grosso. In *3.ª Vitrine Tecnológica Agrícola: Atualidades na Cultura do Milho em Sistema Soja e Milho-safrinha*; de Abreu, D.C., de Lima Dias, M.P., Boscoli, D.Z., da Silva, W.M., de Paula Alberto, F., Martins, A.R.R., Pinheiro, D.T., Eds.; UNISELVA: Cuiabá, Mato Grosso, Brazil, 2022; Chapter 8; pp. 121–144. ISBN 978-65-86743-50-0.
47. Perazzo, A.F.; de Carvalho, G.G.P.; Santos, E.M.; Pinho, R.M.A.; Campos, F.S.; Macedo, C.H.O.; Azevêdo, J.A.G.; Tabosa, J.N. Agronomic evaluation of 32 sorghum cultivars in the Brazilian semi-arid region. *Rev. Bras. Zootec.* **2014**, *43*, 232–237. [CrossRef]
48. Cunha, A.P.M.A.; Zeri, M.; Leal, K.D.; Costa, L.; Cuartas, L.A.; Marengo, J.A.; Tomasella, J.; Vieira, R.M.; Barbosa, A.A.; Cunningham, C.; et al. Extreme Drought Events over Brazil from 2011 to 2019. *Atmosphere* **2019**, *10*, 642. [CrossRef]
49. Sharma, S.; Sharma, M.; Mudgal, D.; Bhowmick, H. Adoption of strategies for clean combustion of biomass in boilers. *Corros. Rev.* **2021**, *39*, 387–408. [CrossRef]
50. *ISO 17225-2*; Solid Biofuels: Fuel Specifications and Classes. Part 2, Graded Wood Pellets, 2nd Edition, Vernier. International Organization for Standardization: Geneva, Switzerland, 2021. Available online: https://www.iso.org/standard/76088.html (accessed on 3 July 2024).
51. *ISO 17225-6*; International Organization for Standardization. Solid biofuels: Fuel Specifications and Classes. Part 6, Graded Non-Woody Pellets. Lithuanian Standards Board: Vilnius, Lithuania, 2021. Available online: https://www.iso.org/standard/76093.html (accessed on 3 July 2024).
52. Brand, M.A. *Energia da Biomassa Florestal*; Interciência: Rio de Janeiro, Brazil, 2010; pp. 1–114, ISBN 8571932441.

53. Engebretsen, S.E. Toxicity and Genotoxicity of five pyrolytic Bio-Oils produced from Wood, measured as Root Growth Inhibition and DNA Double-Strand Breaks in *Allium cepa*. Master's Project, Department of Biology, Norwegian University of Science and Technology. 30 May 2014. Available online: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/245485/733671_FULLTEXT01.pdf?sequence=1 (accessed on 4 July 2024).
54. Vassilev, S.V.; Baxter, D.; Andersen, L.K.; Vassileva, C.G.; Morgan, T.J. An overview of the organic and inorganic phase composition of biomass. *Fuel* **2012**, *94*, 1–33. [CrossRef]
55. Jardim, A.M.d.R.F.; da Silva, G.I.N.; Biesdorf, E.M.; Pinheiro, A.G.; da Silva, M.V.; do Nascimento Araújo Júnior, G.; dos Santos, A.; Alves, H.K.M.N.; de Sá Souza, M.; de Morais, J.E.F.; et al. Production potential of *Sorghum bicolor* (L.) Moench crop in the Brazilian semiarid: Review. *Pubvet* **2020**, *14*, 141. [CrossRef]
56. Pinho, R.V.; Silva, E.V.V.; de Oliveira, T.L.; de Souza, V.F.; de Menezes, C.B. Breeding Sorghum for Grain, Forage and Bioenergy in Brazil. *Rev. Bras. Milho Sorgo* **2022**, *21*, e1275. [CrossRef]
57. Tonapi, V.A.; Talwar, H.S.; Are, A.K.; Bhat, B.V.; Reddy, C.R.; Dalton, T.J. (Eds.) *Sorghum in the 21st Century: Food–Fodder–Feed–Fuel for a Rapidly Changing World*, 1st ed.; Springer Nature Singapore Pte Ltd.: Singapore, 2020; pp. 1–940. ISBN 978-981-15-8248-6/978-981-15-8249-3. [CrossRef]
58. Pereira, C.H.; Patino, H.O.; Hoshide, A.K.; Abreu, D.C.D.; Rotz, C.A.; Nabinger, C. Grazing supplementation and crop diversification benefits for southern Brazil beef: A case study. *Agric. Syst.* **2018**, *162*, 1–9. [CrossRef]
59. Pedrosa, L.M.; Hoshide, A.K.; Abreu, D.C.; Molossi, L.; Couto, E.G. Financial transition and costs of sustainable agricultural intensification practices on a beef cattle and crop farm in Brazil's Amazon. *Renew. Agric. Food Syst.* **2019**, *36*, 26–37. [CrossRef]
60. Morales, M.M.; Tonini, H.; Behling, M.; Hoshide, A.K. The role of forest carbon stock in an integrated livestock-forestry system. *Sustainability* **2023**, *15*, 7750. [CrossRef]
61. Jagtap, A.; Kalbande, S. Pelletization Process for the Production of Fuel Pellets from Various Surplus Biomass: A Review. *Int. J. Environ. Clim. Chang.* **2023**, *13*, 200–208, ISSN 2581-8627. [CrossRef]