scientific reports

OPEN

Energy potential of elephant grass broth as biomass for biogas production

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The growing demand for clean energy has highlighted plant biomass as a valuable alternative, supporting sustainable development goals. Elephant grass (EG) is a promising feedstock due to its adaptability to diverse soils and climates, high dry matter production, and substantial energy yield. This study aimed to evaluate and characterize six selected EG genotypes (BRS Capiaçu, T_23.1, T_23.2, T_41.2, T_47.1, and T_51.5) based on their broth productivity and energy yield. Analysis of the broth's yield and physicochemical properties revealed that the by-product extracted from the biomass had a high residual energy value. Additionally, extracting the broth reduces the grass's biomass moisture content, enhancing its calorific value and improving the bagasse quality for combustion in boilers, thus optimizing energy production. This study demonstrates that the promising EG genotypes T_47.1, T_41.2, and T_23.1 presented relevant energy values ranging from 4248.12 to 4304.06 kcal kg^{-1} of bagasse and thus are suitable for energy production through direct combustion. The extracted broth is a valuable residual energy source that can be utilized industrially after anaerobic digestion. Future research should focus on the environmental and economic effectiveness of EG broth as an energy source from waste and its potential for biogas production.

Keywords Bioenergy, *Cenchrus purpureus*, Environmental biotechnology, Lignocellulosic biomass, Waste-to-energy

Technologies for generating renewable energy are crucial for sustainable development, which requires a reduction in gas emissions, transition from fossil fuel-based power to renewable energy sources, and enhancement of energy efficiency[1]. The increased reliance on fossil fuels has had significant consequences for the planet, including major polluting gas emissions, and intensified climate change[2,3]. Among renewable energy sources, biomass is a viable alternative to fossil fuel derivatives[4].

Driven by the urgent need to combat global warming caused by unchecked greenhouse gas (GHG) emissions, industries are working to replace petrochemical inputs with sustainable, bio-based alternatives[5]. The utilization of plant biomass for energy production is a key strategy for mitigating GHG emissions[6–8].

Biomass from dedicated energy grass crops represents a significant and promising alternative for energy generation. This includes direct combustion[9] and cogeneration through the combined production of thermal and mechanical energy, utilizing specific thermochemical processes[10,11] or biological processes, such as anaerobic digestion[12]. Agricultural wastes can be used for various energy applications, including electricity generation, biofuel production (such as bioethanol), and biogas production[13–16].

Lignocellulosic biomass is the third largest source of energy on the planet and a major abundant renewable carbon sources in nature, making it a suitable candidate for producing biofuels and other value-added products[17]. Carbon-containing biomass can be converted into bioenergy (heat and electrical energy), biofuels, biochemicals, and materials via various processes such as combustion, gasification, pyrolysis, hydrothermal treatment, and biological conversion[18,19]. Therefore, the use of biomass in the development of new renewable energy sources is crucial.

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Among the various biomass sources explored, elephant grass (EG) (*Cenchrus purpureus* [Schumach.] Morrone), a perennial grass native to the tropical grasslands of Africa, is considered a promising and attractive bioresource for applications in various fields, such as agriculture, energy, and materials[20]. This grass adapts well to the climate and soil conditions of nearly all countries in tropical regions, and it is widely regarded as both a forage grass and an energy crop in various tropical regions because of its exceptional growth potential and high biomass yield. Traditionally, EG has been used as forage for livestock owing to its high productivity and nutritional value. However, in recent years, its use has expanded to energy applications such as biogas production, cellulosic ethanol production, and electricity generation, particularly in countries like Brazil, where the demand for renewable energy sources is increasing[21–23].

Currently, EG is one of the most widely used forages in Brazil and several countries in Africa and Asia, including Thailand, Indonesia, and Malaysia. It can grow in various climatic conditions, is drought-tolerant, and produces high yields even on marginal soils, making it an ideal candidate for sustainable biomass energy production. Its rapid growth rate and ability to support multiple harvests make it a cost-effective solution for farmers in both developed and developing countries. Brazilian Agricultural Research Corporation (Embrapa), in 2016 developed the BRS Capiaçu, a cultivar with very high dry matter productivity, and reported that this cultivar yields approximately 50 tons of dry matter per ha.yr^{-1}, which is, on average, 30% more than the yield of other currently available cultivars[24].

Embrapa has developed an EG breeding program for bioenergy, resulting in the development of new cultivars specifically designed for energy production[25–28]. This progress provides valuable insights for identifying and incorporating superior genetic materials into germplasm banks, thereby enhancing genetic improvement programs. To optimize the utilization of available genetic resources, a comprehensive understanding of the relevant characteristics and feasibility of EG as an energy source is crucial for selecting elite genotypes[29]. The genetic selection of high-yield genotypes of EG is important for increasing its use in bioenergy production. The impetus for this work stemmed from the growing demand for sustainable energy alternatives and the potential of EG in bioenergy applications, particularly in biofuels and biogas production.

Recent studies have highlighted the economic viability of using EG as an energy source, demonstrating its potential as a biomass energy matrix[18,30]. The EG biomass is a viable raw material for thermal energy generation because of its desirable qualitative characteristics, where are similar to those of sugarcane bagasse, which is the main raw material for thermal energy derived from plant biomass[15,31]. In Brazil and other parts of the world, private companies use EG as a substrate for electricity generation, cellulosic ethanol production, cellulose, and lignin nanoparticle production in biorefineries, and other high-value biotechnological applications[32–34].

However, the moisture content poses a challenge for thermoelectric plants. The broth extraction process offers a solution by reducing the moisture content of EG biomass, though further studies are required to optimize the utilization of the remaining material[23]. Furthermore, parameters such as ash content and volatile materials content can provide an estimate the behavior of certain types of biomass during direct combustion[35]. The EG broth extraction process can reduce the moisture level and increase the calorific value of the biomass[23]. In this scenario, broth extraction from EG is an excellent alternative for increasing the energy density of biomass. The extraction broth can be utilizaed for the production of biogas, biomethane, biofertilizers, or for other applications[36]. The novelty of this study lies in utilizing energy from waste EG broth as a co-substrate in anaerobic processes. Additionally, the extraction of the broth reduces the moisture content of the grass biomass, which enhances its calorific value and bagasse quality for combustion in boilers, thus optimizing the residue from the thermoelectric process as a new biomass for energy production. Figure 1 illustrates the integrated process, from field evaluation of elephant grass genotypes to biomass energy conversion, highlighting how broth extraction contributes to both biogas production and improved biomass for thermoelectric use, closing the cycle.

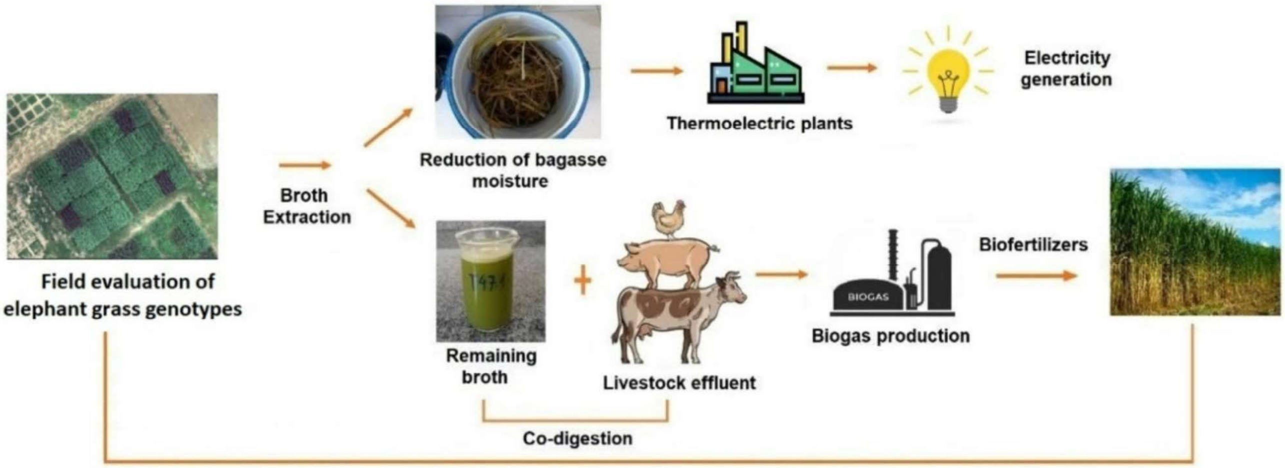

Fig. 1. Schematic representation of the integrated utilization process of elephant grass biomass for bioenergy production.

In the context of total energy utilization from plant biomass, EG is first harvested in the field, processed in mills to extract the broth and remaining bagasse, and then dried at appropriate temperatures. This process reduces the moisture content to a level that allows the immediate use of biomass in bagasse form in direct combustion. However, as the EG cultivation area increased, residues were generated during the preparation of the plant dry biomass. Therefore, this study focused on the residue of EG broth extracted from biomass, which is considered a byproduct of the bioenergy chain and holds potential for the production of biofertilizers and biogas through anaerobic biodigestion[23,29,37]. The objective of this research was to evaluate and characterize EG genotypes based on their broth productivity and energy yield. Additionally, the study aims to validate EG broth as an energy biomass, exploring its potential for anaerobic processes and as a viable alternative for energy production.

Materials and methods

Feedstock sampling

The EG genotypes used in the experiment to evaluate the energy potential of plant biomass and broth extracted for biogas production were collected from the José Henrique Bruschi Experimental Farm, which belongs to Embrapa Dairy Cattle and is located in the municipality of Coronel Pacheco, Minas Gerais, Brazil (21° 33′ 58″ S 43°15′ 21″ W, 445 m above sea level). The region's climate is classified as tropical (Cwa) according to the Köppen and Geiger scale, with an average annual temperature of 22 °C, (maximum 35 °C, minimum 18 °C), and an average annual rainfall of 1516 mm. Climate data were obtained from an automatic weather station located 200 m from the experimental site[38].

In this experiment, six elite genotypes were evaluated: BRS Capiaçu, T_23.1, T_23.2, T_41.2, T_47.1, and T_51.5. These genotypes originated from breeding programs developed by Embrapa focusing on bioenergy production. Embrapa Dairy Cattle Research Center maintains an Active Elephantgrass Germplasm Bank (BAGCE). The study was conducted in accordance with the guidelines and legislation outlined in the IUCN Policy Statement on Research Involving Species at Risk of Extinction and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

At 125 days after planting, the grass genotypes were harvested by cutting at a height of 0.25–0.28 m from the soil surface using pruning shears. The mass of ten whole plants from each genotype was initially measured to evaluate the productivity of each genotype. To determine broth yield, the plants were ground in a semi-industrial mill with stainless-steel rollers, the broth was collected, and its volume (mL) was recorded. The biomass residue from the pressed bagasse was also weighed, resulting in the broth volume-to-mass ratio for each genotype (mL kg^{-1}), as shown in Fig. 2.

Physicochemical analysis

The chemical and physical composition of the plants, broth, and bagasse of the EG genotypes was analyzed. To characterize each genotype, the following traits were determined: total soluble solid content (°Brix), which was quantified using a digital refractometer (model MA871); total solids (TS), volatile solids (VS), fixed solids (FS),

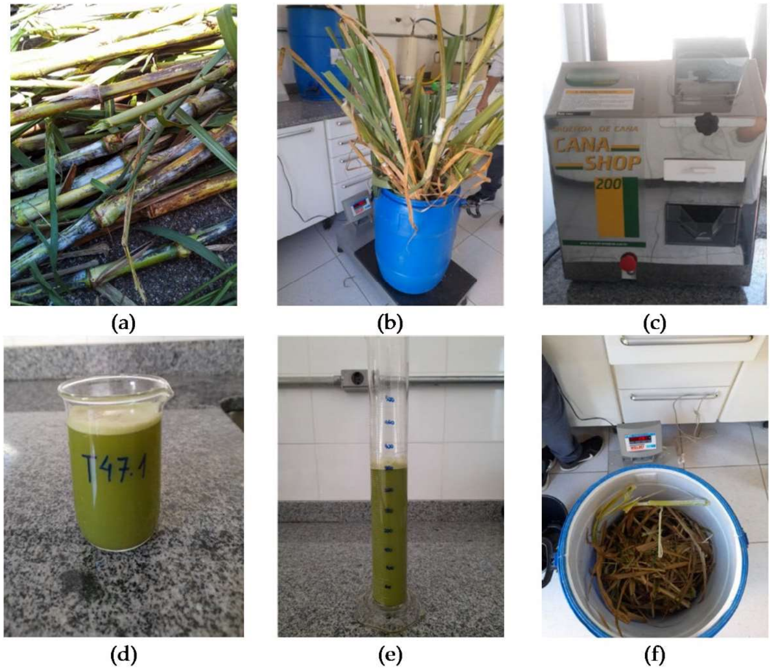

Fig. 2. (**a**) The genotypes separated and identified; (**b**) measured the weight of ten whole plants of each genotype; (**c**) semi-industrial mill with stainless steel rollers; (**d**) broth was collected; (**e**) measuring the volume (in ml); and (**f**) measured the weight of pressed bagasse biomass waste.

alkalinity, and pH, were analyzed in triplicate using standard methods[39] and NBR 8112[40]. The calorific value was determined based on raw energy analyses performed in a calorimetric bomb after crushing the samples, which were performed in duplicate according to NBR 11956[41]. The dry biomass results were expressed in kilocalories per kilogram (kcal kg $^{-1}$), and the broth results were expressed in calories per kilogram (cal kg $^{-1}$).

The productivity, yield, and physicochemical composition of the bagasse were compared among the EG genotypes. Subsequently, the physicochemical composition of the EG broths was compared. Previous studies carried out by Embrapa were used to support the development of the experimental method[14,42].

Statistical analysis

The experimental design involved six genotypes (plant biomass) with three replications. Differences in the means were evaluated based on analysis of variance (ANOVA) followed by Tukey's test for mean comparisons at a 5% significance level ($p \leq 0.05$) using PAST 4.03 software.

Results and discussion

Productivity and quality of the plant and Bagasse

In this study, the broth yield from the EG varieties ranged from 66.7 mL kg $^{-1}$ (T23.1) to 189.1 mL kg^{-1} (T_23.2). The superior performance of the T_23.2 genotype in terms of plant productivity (kg) and broth yield (mL kg^{-1}), highlighted its significant energetic potential, including the possibility of utilizing the remaining broth (Table 1). After extracting the broth from the six cultivars, the average water content of the different materials was 16%. As shown in Table 1, genotypes T_41.2, T_47.1, and T_23.1 had the lowest water content values, close to the ideal value (12%) reported in the literature[43,44]. Water content is a critical factor for the use of biomass in energy applications. Higher moisture levels in lignocellulosic materials are inversely correlated with their calorific value because more energy is spent on evaporating water during combustion rather than generating heat[45].

Therefore, it can be concluded that EG bagasse has a lower moisture content than other studied biomasses. Singh[46] reported that the water content in sugarcane bagasse after mill processing in a crushing plant was approximately 50%. Similarly, Marx et al.[19] reported that sugarcane bagasse had higher humidity than the other samples analyzed in their study. Thus, agricultural waste with lower moisture levels has greater energy efficiency and is more suitable for bioenergy production via direct combustion, as it produces more dry matter.

The bagasse from the tested genotypes contained, on average, 95% dry matter, confirming that the species is an excellent alternative for cultivation dedicated to energy biomass production (Table 1). The EG cultivars are primarily characterized by high dry matter production[47] and represent important tropical forage with the potential to become an alternative feedstocks for energy production[48]. Generally, biomass contains high levels of volatile compounds[49]. Literature data indicate that biomass contains up to 2.5 times more volatile matter than coal, which is an important parameter to consider in terms of ignition and combustion[50].

The dry matter, ash, and raw energy contents of the bagasse showed significant differences between the feedstocks, as presented in Table 1. Notably, the BRS Capiaçu genotype had significantly higher ash content than the other genotypes at 7.22%, while the EG T_41.2 variety had the lowest ash content at 3.69%. The mean ash content across all EG a variety was 5.38%, which was within the desired range for use in direct combustion. High ash levels in biomass (> 5%) are generally undesirable for combustion processes[51]. The genotypes T_47.1, T_41.2, and T_23.1 presented the lowest ash content values, which were all below 5%. This result is relevant for the selection of biomass for electricity generation, which takes place inside thermoelectric plants that burn bagasse. The values found in this study were close to those in a previous report[15], where the EG ash content values ranged from 3.21% (EG, genotype Madeira) to 6.14% (EG, genotype Pasto Panama). In their study, the authors investigated the chemical composition and calorific value of EG varieties and other feedstocks intended for

Genotype	Parameters							
	Gw	Bw	Wc	Veb	By	Dm	Ac	Re
BRS Capiaçu	2.7	2.2	18.5	350	131.5	95.00 ^{b} (0.01)	7.22 ^{a} (0.02)	4041.14 ^{d} (0.51)
T23.1	1.5	1.3	13.3	100	66.7	94.95 ^{b} (0.01)	4.84 ^{d} (0.01)	4296,93 ^{a} (0.19)
T23.2	4.6	3.6	21.7	870	189.1	95.60 ^{a} (0.01)	5.80 ^{c} (0.03)	4206.84 ^{c} (0.07)
T41.2	2.5	2.2	12.0	245	98.0	95.47 ^{ab} (0.01)	4.81 ^{d} (0.01)	4248.12 ^{b} (0.20)
T47.1	2.3	2.0	13.0	260	113.0	95.03 ^{b} (0.01)	3.69 ^{e} (0.02)	4304.06 ^{a} (0.65)
T51.5	2.4	2.0	16.6	250	104.2	95.55 ^{ab} (0.25)	5.92 ^{b} (0.02)	4232.68 ^{b} (0.47)

Table 1. Productivity, yield, and physicochemical composition of pomace from elephant grass genotypes. *Gw*: Grass weight (kg); *Bw* - Bagasse weight (kg); *Wc* - Water content (%); *Veb*: Volume of extracted broth (ml); *By* - Broth yield (ml kg $^{-1}$); *Dm* - Bagasse dry matter content (%); *Ac* - Bagasse ash content (%); *Re* - Raw Energy (kcal kg $^{-1}$). Values in parentheses indicate the standard deviations. Mean values followed by the same letters within each column do not differ statistically from each other according to Tukey's test at the 5% significance level.

direct combustion and found that the average ash content of EG varieties was comparable to that of corn stover, bamboo, and sugarcane. García-Montoya et al.[52] analyzed the potential of three sugarcane bagasse varieties as agricultural residues for bioenergy use and reported average ash values of 6.20%.

Knowledge of ash content in biomass is crucial for implementing preventive measures to mitigate corrosion during combustion in boilers. Low ash values in biomass are desirable because it is the main substance that generates scale in boilers and furnaces in the sugarcane and ethanol industries[53]. At high combustion temperatures, ash deposits reduce the heat-transfer efficiency of the heating surface, compromising the operational safety of the boiler[54,55].

In summary, low ash content values are relevant for the use of biomass as an alternative energy because high amounts of ash reduce the calorific value and lead to energy loss[56,57]. When biomass is subjected to high combustion temperatures, ash can negatively influence the performance and durability of the equipment used in the energy conversion process. We also observed that the gross energy values of genotypes T_47.1, T_41.2, and T_23.1 were inversely proportional to their ash content values, which is consistent with the literature. Thus, these genotypes present excellent energy potential and low ash content (Fig. 3).

A higher heating value is a crucial property of biomass for its use as a fuel. A bomb calorimeter was used to analyze its calorific value, which is a parameter that reflects the amount of heat released during the complete combustion of a material[58]. The raw energy values of the studied genotypes ranged between 4041.14 and 4304.06 kcal kg $^{-1}$ (Table 1) and were calculated based on the heat of combustion determined by the calorimetric method using a Parr Adiabatic Oxygen Bomb Calorimeter. Similar values were reported by Marafon et al.[14], who obtained values between 4209 and 4400 kcal kg $^{-1}$ for 18 EG varieties. Rocha et al.[26] evaluated the suitability of the Cameroon and Napier groups to breed EG for the production of bioenergy via direct combustion and found values of 4325 kcal kg $^{-1}$ for the Napier group and 4437 kcal kg $^{-1}$ for the Cameroon group. Similarly, Martins et al.[59] evaluated the energy values of green EG harvested at 56, 84, and 112 d of age and found raw energy values of 4030, 4030, and 4040 kcal kg $^{-1}$ of dry matter in the grass, respectively. The raw energy values observed in these studies were similar to the results found in our study, affirming the potential of EG species via the direct combustion of biomass.

The genetic selection of high-productivity EG genotypes is important for increasing the use of this biomass for energy generation. Rocha et al.[60] investigated the genetic improvement of EG for bioenergy production and evaluated the potential of genotypes for energy cogeneration. Generally, morpho-agronomic characteristics, physicochemical composition, and calorific value are essential for determining the quality of biomass for heat generation because these parameters influence the entire process of conversion and thermal utilization[15]. Thus, the growing interest in raw materials for bioenergy production has highlighted EG as a promising energy source[27].

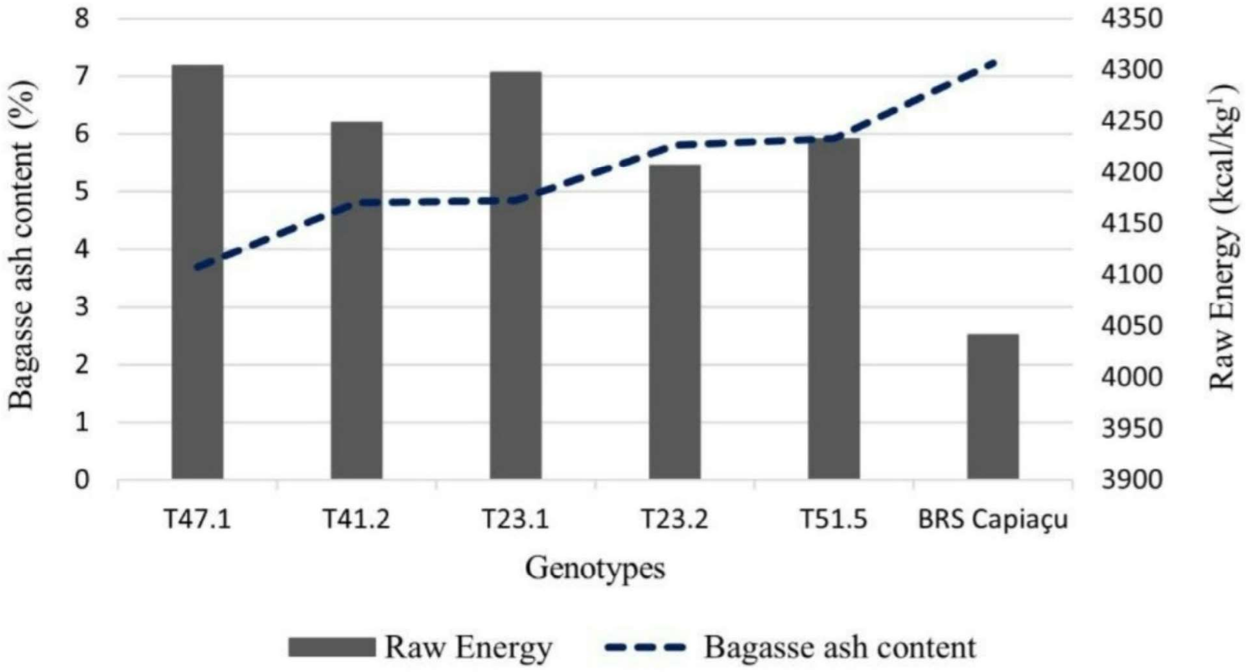

Fig. 3. Production of raw energy (kcal kg $^{-1}$) was presented in columns. The Bagasse ash content values (%) was presented in lines. The highest value of one corresponds to the lowest of another.

Genotype	Parameters					
	°Brix	pH	TS	FS	SV	EB
BRS Capiaçu	7.30 ^{c} (0.08)	5.64 ^{a} (0.02)	7.38 ^{d} (0.04)	1.30 ^{a} (0.01)	6.08 ^{d} (0.02)	307.16 ^{c} (0.30)
T23.1	7.20 ^{c} (0.05)	5.45 ^{cd} (0.02)	8.56 ^{c} (0.01)	1.02 ^{c} (0.01)	7.54 ^{c} (0.01)	391.72 ^{b} (0.56)
T23.2	8.70 ^{a} (0.10)	5.39 ^{d} (0.01)	6.98 ^{e} (0.03)	0.97 ^{d} (0.01)	6.20 ^{d} (0.03)	302.10 ^{d} (0.85)
T41.2	8.55 ^{a} (0.18)	5.51 ^{bc} (0.01)	8.77 ^{b} (0.03)	0.72 ^{e} (0.01)	8.05 ^{a} (0.03)	409.99 ^{a} (0.84)
T47.1	7.60 ^{c} (0.15)	5.42 ^{d} (0.02)	9.11 ^{a} (0.03)	1.19 ^{b} (0.01)	7.92 ^{b} (0.03)	392.57 ^{b} (0.67)
T51.5	8.15 ^{b} (0.04)	5.57 ^{ab} (0.05)	7.07 ^{e} (0.02)	1.20 ^{b} (0.02)	5.87 ^{e} (0.01)	293.14 ^{e} (0.12)

Table 2. Physicochemical composition of elephant grass genotype broth. *°Brix* - Total soluble solids content; *TS* - Total solids (%); *FS* - Fixed solids (%); *VS* - Volatile solids (%); *Re* - Raw Energy (kcal kg $^{-1}$).The values in parentheses indicate standard deviation. Mean values followed by the same letters within each column do not differ statistically from each other by Tukey's test at a 5% significance level.

In the industrial processing of biomass, an increase in humidity beyond the projected operating limits leads to system instability due to the considerable reduction in temperature in the combustion zone. Water content is a fundamental parameter in thermochemical processes, and a low water content contributes to a high calorific value. The higher the water content, the lower the amount of energy available for combustion. Although combustion reactions are typically exothermic, releasing energy in the form of heat to the surroundings, water vaporization is an endothermic process that absorbs energy[61].

Productivity and quality of the broth and energy utilization

Currently, the most commonly used technology in Brazilian sugar and ethanol plants for producing thermal and electrical energy is the direct combustion of sugarcane bagasse and straw in boilers[62]. In this context, EG bagasse could serve as a supplementary alternative for improving the energy efficiency of direct combustion in sugarcane industries. Therefore, investing in and implementing biomass pre-treatment and drying systems, such as the extraction of grass broth, would provide benefits associated with improving energy efficiency and lead to significant savings by reducing boiler maintenance costs.

In the search for new alternative energy supplies, extracted EG broth has been revealed as a substrate in anaerobic digestion processes for biogas production. This broth contains nutrients that can be used in industry and microbial fermentation for bioenergy production. Biogas production in plants can generate financial returns, contribute to environmental sustainability, and support a circular economy[63,64].

The main advantages of extracting EG broth include reducing moisture content, increasing the calorific value of biomass, and potentially using the energy remaining in the broth for biogas production[42], biofertilizers, or other applications. The broth extracted from each genotype was characterized according to its physicochemical composition, as shown in Table 2. Regarding the total soluble solid content (°Brix) of the broth, the genotypes varied from 7.20 to 8.70, with the T_23.2 genotype having the highest value. Similar results were observed by Marafon and Machado[42], who verified that the sugar content values in six EG accessions after 180 d of growth varied between 5.50 and 7.50 °Brix. These results are consistent with those of Cunha et al.[65], who evaluated °Brix in 95 accessions from the EG germplasm and the effect of plant age on sugar concentration. Lignocellulosic biomass represents the most abundant renewable carbon resource. It is mainly composed of cellulose, hemicellulose, and lignin, making it an excellent source of fermentable sugar. These characteristics must be considered when using EG broth, such as in the anaerobic digestion process[28,66].

Pre-treatment methods for lignocellulosic biomasses have been extensively studied to enhance biogas production by the digestion of lignocellulose-based materials[67,68]. The pH is one of the main operational factors that significantly affects the anaerobic digestion process. Previous research has reported that pH values less than 6.6 inhibit the growth of methanogenic archaea[69,70]. Our results corroborate the acidic pH of the broth of the genotypes and are consistent with the findings of Marafon and Machado[42].

Kunz et al.[71] have suggested that the ideal intermediate alkalinity (IA) to partial alkalinity (PA) ratio for anaerobic digestion varies between 0.3 and 0.4. The IA/PA ratio is useful for identifying possible inhibition triggered by excessive acidification during the anaerobic digestion process. This parameter is commonly used as an index of process stability in biodigesters, with higher values indicating acid accumulation and the occurrence of disturbances in the digestion stability and lower values ensuring the maintenance of the buffer system[72]. The IA/PA values found in this study were 0.69 (BRS Capiaçu), 0.77 (T_23.1), 0.76 (T_23.2), 0.82 (T_41.2), 0.75 (T_47.1), and 0.76 (T_51.5), which were all above the recommended limit. Thus, the acidic nature of the broths from the analyzed genotypes may represent a limiting factor for the direct production of biogas. However, this characteristic may indicate the potential use of EG in anaerobic co-digestion.

Although EG broth is a by-product of the bioenergy chain and a liquid substrate rich in carbon and minerals, its low pH and high acidity content slows down the digestion process owing to the increase in volatile fatty acids (VFAs), which makes it resistant to biological processes[37]. To address this, co-digesting lignocellulosic biomass with nitrogen-rich feedstock can maintain an ideal C/N ratio for anaerobic processes[73].

Ruminant waste, particularly from cattle, serves as a good substrate for biogas production because it contains methanogenic microorganisms that act as an inoculum during the fermentation phase[38,74]. Traditionally, animal waste has been used as the main substrate in anaerobic processes; however, the high nitrogen content of such waste poses an obstacle to maintaining the optimum C/N ratio required for anaerobic digestion[75,76]. High nitrogen content can lead to highly toxic levels of ammonia[77,78]. Because animal manure has a low carbon concentration, this deficit can be detrimental to anaerobic digestion in relation to the C/N ratio. To resolve this issue, the carbon content must be increased before anaerobic digestion can proceed[79]. Therefore, animal manure must be co-digested with materials rich in organic carbon, such as carbonaceous residues, to compensate for the carbon deficit of cattle manure[80].

Silva et al.[38] demonstrated that the co-digestion provides fundamental and technical insights for the sustainable co-treatment of industrial waste in centralized anaerobic biodigestion facilities with high process capacity and methane recovery. Anaerobic co-digestion has been widely used to increase biogas production in digesters, where two or more types of organic waste are often mixed to increase biogas production[81]. For instance, studies have utilized EG biomass in the bioprocess, such as Freitas et al.[82], who conducted a Life Cycle Assessment on the co-digestion of pig manure with two co-substrates, corn silage and EG, along with an additive (biochar) to produce biogas for electricity generation. Similarly, Silva et al.[28] evaluated biogas production from the anaerobic co-digestion of EG broth with vinasse in a batch reactor. The results showed efficient anaerobic digestion under mesophilic conditions without pre-treatment.

Recent research has explored various methods to optimize biogas and bioenergy production, including enzymatic pre-treatment for the co-digestion of sugar beet pulp silage and vinasse[83], co-digestion of pressed sugarcane residue with vinasse to boost methane yield[84], recycling cellulose alcoholic fermentation vinasse to enhance bioenergy recovery[85], and co-digestion of sewage sludge, poultry manure, and swine manure to produce biohydrogen[86].

The total solid content of EG broth was less than 10% (Table 2), which corresponds to the characteristics required for good biodigester functioning; thus, EG broth is a suitable substrate for wet anaerobic digestion, which supports optimal hydrodynamic conditions[71]. However, the lignocellulose composition can be a limiting factor in the hydrolysis stage of anaerobic digestion, and enzymatic degradation of the biomass may require long time periods[87].

It is important to highlight the use of EG broth with low total solids as a substrate for anaerobic digester to avoid operational issues such as clogging, floating layers in the digester[88], and recalcitrance of the solid to enzymatic degradation[89]. The volatile solids content averaged 87% of total solids, representing a high amount of organic matter available for fermentation (Table 2). The extraction of broth in mills significantly reduces water and mineral nutrient content (constituents of ash) and improves the quality of the solid fuel (bagasse) by increasing its calorific value.

The internal energy contained in biomass, which indicates the amount of heat generated per kilogram of biomass, is crucial in industry. The results of the broth gross energy analysis demonstrated that energy remains after extraction, making EG a valuable substrate for co-digestion. The genotypes T_41.2, T_47.1, and T_23.1 had the highest gross energy values (Table 2), making them suitable for use as a substrate in the anaerobic co-digestion process. Notably, anaerobic co-digestion, by combining two or more substrates, can increase biogas production and balance the disadvantages of using a single substrate[90].

Anaerobic co-digestion holds great potential for improving the digestibility of various raw materials, facilitating waste management, and generating bioenergy and other high-value products[91]. However, further research is needed to develop new approaches to characterize raw materials as substrates and better understand the microbial community dynamics and associated pathways in substrate degradation. In this context, EG broth is a residue with significant potential for use as the remaining biomass in industrial and agricultural processes. Further research on co-digestion is crucial to fully exploit the potential of EG broth, which is promising for waste management and renewable-energy generation.

Conclusions

The remaining energy in the broth extracted from EG indicates its value as an alternative substrate for biogas production through anaerobic fermentation, particularly when combined with co-digestion alongside another substrate of interest. Furthermore, broth extraction reduces the moisture content and improves the quality of the solid fuel (bagasse) by increasing its calorific value. On an industrial scale, genotypes T_47.1, T_41.2, and T_23.1 presented satisfactory bagasse ash content (%) and raw energy (kcal kg^{-1}) for energy efficiency.

The EG T_23.2 genotype displayed favorable results for the volume of extracted broth (mL) and broth yield (mL kg^{-1}). However, the physicochemical composition analysis revealed that the genotype T_41.2 had significantly higher volatile solids (%) and raw energy (cal kg^{-1}) values, values compared with those of other genotypes. These parameters are essential for anaerobic digestion efficiency. Overall, all studied genotypes were considered suitable for energy purposes, with the potential to use the remaining broth as a co-substrate in anaerobic co-digestion process, offering bioenergetic advantages.

The T_47.1, T_41.2, and T_23.1 varieties demonstrated the best results for energy applications, maximizing biomass utilization on an industrial scale, followed by anaerobic digestion of the broth. Future research should evaluate the environmental and economic effectiveness of EG as an energy source derived from waste, with a focus on biogas production.

Data availability

All data generated or analyzed during this study are included in this published article in the form of figures, tables and graphs. The data that support the findings of this study are available from the corresponding author, J.C.M., upon reasonable request.

Received: 3 December 2024; Accepted: 24 February 2025

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Acknowledgements

The authors thank the Federal University of Viçosa, Brazilian Agricultural Research Corporation (Embrapa Dairy Cattle), project and funding agencies: National Council of Technological and Scientific Development (CNPq), the Foundation for Research Support of the State of Minas Gerais (FAPEMIG), and the Coordination for the Improvement of Higher Level or Education Personnel (CAPES) for their cooperation during the study and financial support.

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Funding

This work was supported by Embrapa (20.18.01.016.00.07.004 and 20.23.00.105.00.00) and the National Council of Technological and Scientific Development (CNPq; Process: 406835/2022-5 and 402679/2022-9). Scholarship by the Coordination for the Improvement of Higher Level or Education Personnel (CAPES) – Finance Code 001 and Scholarship PhD Exterior (SWE) Process: 200150/2022–7 Call 26/2022. Foundation for Research Support of the State of Minas Gerais (FAPEMIG) – Codes APQ-00731-18, APQ-03630-23, and scholarship CI: CRD-00169-21.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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