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Assessment of energy potential of sugarcane bagasse (*Saccharum officinarum*) for solid biofuel production in a small-scale enterprise in Junín, Manabí, Ecuador

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ABSTRACT

The aim of this study was to evaluate the energy valorization potential of sugarcane bagasse generated in the artisanal production of sugarcane liquor by small and medium-sized enterprises (SMEs) in Junín, Manabí, Ecuador. Field measurements confirmed that the milling and extraction stage constitutes the critical point of bagasse generation, producing 0.415 kg of wet bagasse per kg of processed sugarcane, corresponding to 41.54% of the cane mass. This predictable and significant biomass flow establishes a reliable feedstock for energy recovery in local production systems. Proximate characterization revealed a high initial moisture content (46–56%), high volatile matter (~84%), and variable ash content (2.82–5.51%), indicating the need for preconditioning steps such as drying and impurity reduction to ensure a stable and high-quality fuel. Controlled densification of bagasse into briquettes resulted in products with low final moisture (8.89–9.69%), reduced ash content (2.14–3.22%), and competitive higher heating values (17.91–18.40 MJ/kg). Among the evaluated formulations, treatment T1 exhibited the best overall performance by combining low moisture, lower mineral fraction, and high energy content, demonstrating that optimized processing can significantly improve fuel quality and stability. The results confirm the hypothesis that controlled densification enhances both the energy and physicochemical properties of sugarcane bagasse, providing a practical and scalable approach for SMEs to recover energy from agro-industrial residues. Beyond demonstrating technical feasibility, this study highlights the potential of local circular economy strategies, showing that systematic bagasse management can reduce environmental impacts, prevent waste generation, and produce valuable bioenergy. By quantifying the relationship between biomass generation, conditioning, and the performance of densified fuel, this work provides new empirical evidence for sustainable bioenergy applications in small-scale contexts, establishing sugarcane bagasse as a viable, low-cost, and locally available solid biofuel.

Keywords: sugarcane bagasse, briquettes, physicochemical characterization, calorific value.

INTRODUCTION

Despite the growing interest in the valorization of sugarcane bagasse, most studies have focused on large-scale biorefinery schemes, centralized processing models, and techno-economic evaluations for high-capacity facilities. For instance, the development of small-scale biorefineries has been proposed to add value to sugarcane bagasse through the integrated production of chemicals and energy. However, assessments of technical feasibility under the conditions of small producers or small and medium-sized enterprises (SMEs) remain limited, particularly in terms of operational constraints, feedstock variability, and process optimization at the local scale, including pathways such as autohydrolysis, xylose and xylitol production, and energy generation (Clauser et al., 2016). Similarly, comprehensive reviews of briquetting processes have described the main densification technologies—hydraulic, mechanical, and screw presses—as well as the influence of process variables such as pressure, particle size, and moisture content on fuel properties, including density and mechanical strength (Marreiro et al., 2021). Nevertheless, although these studies provide a robust technical and conceptual foundation, empirical evidence remains limited regarding the actual performance of these methods when implemented under small-scale conditions and within the technological constraints typical of small enterprises, where access to automated or optimized equipment is restricted and feedstock characteristics are highly variable. Furthermore, while some studies have reported improvements in bulk density and combustion characteristics through co-densification and binding strategies, these experiments have been conducted primarily under controlled laboratory or pilot conditions and do not systematically address the effects of local processing conditions on the calorific value and physicochemical properties of densified bagasse fuels (Navalta et al., 2020).

Consequently, a knowledge gap persists regarding the practical application and optimization of solid biofuel production from sugarcane bagasse in small-scale, resource-constrained contexts, particularly in developing regions. This limitation is especially relevant in territories where sugarcane processing generates recurrent flows of bagasse but lacks adequate waste management or energy recovery strategies. In such contexts, the energy potential of bagasse is often wasted when the residue is abandoned or openly burned, a practice that increases avoidable emissions and contributes to air and soil degradation. Open burning of sugarcane residues has been shown to emit significant amounts of gaseous pollutants, including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), particulate matter (PM), and polycyclic aromatic hydrocarbons (PAHs), all of which contribute to regional air pollution and adverse environmental and health outcomes (Mugica-Álvarez et al., 2018). These emissions are recognized sources of greenhouse gases and toxic compounds that degrade air quality and increase respiratory health risks in exposed populations (Manrique et al., 2025). In this regard, the controlled energy recovery of bagasse through thermochemical routes—such as combustion in boilers, gasification, or pyrolysis—represents an opportunity to more efficiently harness the intrinsic energy content of biomass while reducing uncontrolled emissions associated with open burning. In particular, pyrolysis and gasification processes allow the conversion of bagasse into heat, syngas, biochar, and other useful energy carriers, while reducing pollutant release compared to unmanaged combustion (Ajala et al., 2021). Therefore, valorizing bagasse for energy recovery can provide multiple benefits, including reduced environmental impacts from improper disposal, enhanced local energy availability, and potential cost savings in domestic or productive thermal applications (Ungureanu et al., 2022; Matsueda and Antunes, 2024).

In Ecuador, sugarcane maintains both productive and territorial relevance, with official records of cultivated area and production reported by the National Institute of Statistics and Census through the Continuous Agricultural Surface and Production Survey (ESPAC) (INEC, 2025). In Manabí, and particularly in the canton of Junín, agroproductive dynamics and artisanal processing systems associated with sugarcane generate bagasse on a recurring basis, especially in small-scale units with technical limitations for its integral management (Cartay Ángulo et al., 2019). In rural areas such as the community of Agua Fría, these conditions often lead to inefficient disposal practices, including open burning or abandonment of the residue, which aggravate local pollution problems and waste a potentially valuable energy resource, in contradiction with the principles of circularity and waste recovery (Ellen MacArthur Foundation, 2013; Ungureanu et al., 2022). From a technological perspective, the production of solid biofuel from bagasse generally involves operations such as drying, size reduction, compaction—with or without binder—and, when improved stability and thermal performance are desired, controlled carbonization. These processes directly influence key fuel quality parameters, including moisture content, bulk density, mechanical strength, ash, volatile matter, fixed carbon, and calorific value. Previous studies have indicated that densified bagasse can achieve competitive calorific values exceeding those of untreated biomass, confirming its viability for thermal applications in rural and peri-urban contexts (Mekonen et al., 2024; Suttibak et al., 2024). However, the translation of these findings to rural SME contexts remains limited, as variations in feedstock resulting from harvesting, handling, extraction practices, production scale, and local technological availability can substantially affect the final properties of the fuel and its energy performance. In this context, the main knowledge gap does not lie in the general feasibility of bagasse as a bioenergy feedstock, which has already been widely demonstrated, but rather in the lack of empirical evidence on how feedstock variability and real processing conditions in resource-constrained rural SMEs influence the physicochemical quality, calorific value, and practical energy performance of densified bagasse fuels. Addressing this gap is essential for determining whether solid biofuel production from sugarcane bagasse can be technically viable under realistic small-scale operating conditions and for identifying processing pathways adapted to local contexts. Accordingly, the aim of this study was to evaluate the energy valorization of sugarcane bagasse generated in an SME in Junín, Manabí, Ecuador, by analyzing the relationship between local processing conditions and the physicochemical and calorific properties of densified solid biofuel. Specifically, the study sought to determine whether controlled densification under real small-scale operating conditions improves fuel quality indicators and energy performance compared to untreated residue. We hypothesized that, despite the technological limitations typical of rural SMEs, appropriate conditioning and densification of bagasse would reduce moisture and ash content, improve calorific performance, and produce a technically viable solid biofuel for local energy use. In this way, the study provides new empirical evidence on the practical valorization of agro-industrial residues in non-industrial contexts and contributes to the development of locally adapted circular bioenergy strategies.

MATERIALS AND METHODS

Location

The research was conducted in a small-scale artisanal liquor distillery (SME) located in the canton of Junín, Manabí, Ecuador, with an estimated processing capacity of 2.000–3.000 kg of sugarcane per day. The study area (Figure 1) is situated at 0°54′27” S, 80°11′16” W (WGS84 datum), at an elevation of 48 m above sea level. The experiments were carried out between June and November, corresponding to the sugarcane harvest season in the coastal region of Ecuador, which ensured the representativeness of bagasse properties under real operating conditions. The research was carried out under a descriptive, analytical and experimental approach, aimed at the physicochemical characterization of solid biofuel (briquettes). Through quantitative procedures and experimental tests, the solid biofuel properties and energy potential were evaluated.

Diagnosis of bagasse generation, management and use (SME, Junín canton)

Bagasse generation was characterized using a standardized process survey and a flowchart based on ISO 10628:2014. Shift generation was quantified by direct weighings using calibrated digital scales (precision ±0.01 kg) and consolidated across three independent trials, with matter balance applied as described by Felder et al.

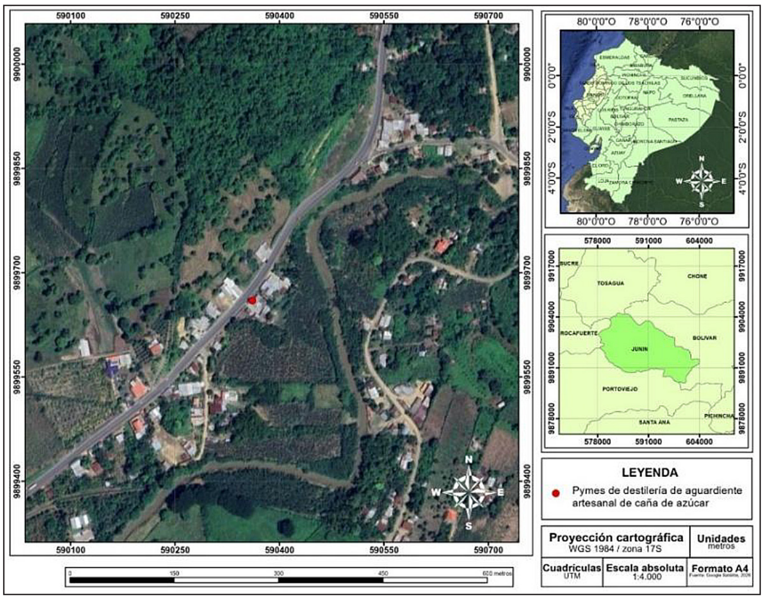

Figure 1. Location of the SME (Small and medium-sized liquor distillery company in the canton of Junín

(2015). Sampling points and mass flows were selected to represent all process stages.

Quantification of bagasse generation and calculation of the overall generation factor

The generation of wet bagasse was quantified through three independent one-pass milling tests, representative of the artisanal operation of the evaluated system. In each trial, 10.20, 22.50, and 40.00 kg of sugarcane were processed, respectively, for a total of 72.70 kg. The mass of cane fed into the mill and the mass of wet bagasse collected at the end of extraction were determined by direct weighing using a calibrated digital balance (±0.01 kg), maintaining a uniform weighing criterion to ensure comparability among runs. The milling tests were conducted at an estimated average processing rate of 12 kg/min under typical ambient conditions for the study area (28 ± 2 °C and 78 ± 5% relative humidity). The moisture content of the generated bagasse ranged from 46.27% to 55.73% (wet basis), with an average of 51.5%, according to proximal characterization.

Juice mass was estimated by difference (mjuice=mcane−mbagasse)(m_{juice}=m_{cane}-m_{bagasse})(mjuice=mcane−mbagasse), following the principle of mass balance applied to the milling operation, where processed biomass is mainly distributed between the extracted liquid fraction and the remaining fibrous residue (Agunloye and Usman, 2023; Bizzo et al., 2014). Likewise, bagasse-to-sugarcane yield was calculated as (mbagasse/mcane)×100(m_{bagasse}/m_{cane})\times 100(mbagasse/mcane)×100, in accordance with technical criteria for the characterization of lignocellulosic by-products from the sugarcane agro-industry (Feedipedia, n.d.; Loh et al., 2013). Subsequently, a global wet bagasse generation factor (Fbg=Σbagasse/Σcane) (F_{bg}=\Sigma bagasse/\Sigma cane) (Fbg=Σbagasse/Σcane) was estimated in kg/kg from the weighted average of the total masses processed in the three trials, as this provides a more representative measure of overall operational performance. This coefficient was used to extrapolate bagasse generation at different processing scales (1 kg, 40 kg, 100 kg, and 1 ton of sugarcane) for collection, drying, and recovery planning, considering bagasse as one of the most relevant co-products of sugarcane processing and a raw material with high energy and material valorization potential (Mann, 1984; Bizzo et al., 2014; Ungureanu et al., 2022).

Sample sampling and preparation

Bagasse samples were collected following ASTM E1757-01 to ensure their representativeness. A total of approximately 30.20 kg of wet bagasse was collected from three independent one-pass milling trials, in which 72.70 kg of sugarcane were processed under representative operating conditions of an artisanal system. The bagasse was manually cleaned to remove visible impurities (soil and non-fibrous fragments) prior to conditioning. The initial moisture content of the material ranged from 46.27% to 55.73% (wet basis), with an average value of 51.5%, highlighting the need for a drying pre-treatment for subsequent valorization. The drying process included a solar drying stage for 3 consecutive days (≈10 h/day, estimated ambient temperature of 30–35 °C), followed by controlled oven drying (Memmert UFE500) at temperatures between 35 and 60 °C for 180 min, until suitable handling conditions were achieved. Subsequently, the dried material was milled using a domestic-type grinder (Oster/MS300) to obtain a particle size ≤3 mm, suitable for densification processes and physicochemical characterization (Figure 2).

Determination of physicochemical parameters of the biomass/by-product

Bagasse was conditioned and checked for suitability by close analysis, considering that moisture is a critical factor of the mechanical quality of densification and usually requires bounded ranges (e.g., ~8–12% as the overall reported value; and 5–10% reported for bagasse briquettes) (Kpalo et al., 2020; Mekonen et al., 2024)." The methods were the ISO/UNE-EN ISO standardized methods (Table 1). Results were reported in % w/w and, when applicable, on a dry basis (bs) (Figure 3).

Solid biofuel processing

Briquettes were formed by pressing 50 g of conditioned bagasse with 20% cassava starch binder in cylindrical molds (diameter 70.68 mm, length 50 mm) using a laboratory-scale manual hydraulic piston briquetting press (custom-built) at approximately 160 kPa for 90 s. post-press drying was performed on ventilated steel trays at 28–32 °C for ~72 h until constant mass was reached (Figure 4).

Figure 2. Missing title

Figure 3. Missing title

Table 1. Method analysis of physicochemical parameters of biomass

Parameter	Reference method	Main condition of the trial	Calculation formula
Humidity (%)	ISO 18134-2:2024 / UNE-EN ISO 18134-2:2024	Oven dry at 105 ± 2 °C to constant mass	M_ar (%) = [(m2 − m3) / (m2 − m1)] × 100
Volatile matter (% w/w, bs)	ISO 18123:2023 / UNE-EN ISO 18123:2024	Sample heating in crucible with lid at 900 ± 10 °C for 7 min, mostly out of contact with air	V_d (%) = { [100 × (m2 − m3) / (m2 − m1)] − M_ad } × [100 / (100 − M_ad)]
Ashes (% w/w, bs)	ISO 18122:2022 / UNE-EN ISO 18122:2023	Calcination in muffle with standard final temperature of 550 ± 10 °C	A_d (%) = [(m3 − m1) / (m2 − m1)] × 100 × [100 / (100 − M_ad)]

Figure 4. Missing title

In Figure 5, the production of briquettes from sugarcane bagasse was carried out based on biomass densification schemes (Tumuluru et al., 2011), incorporating feedstock conditioning stages to ensure homogeneity and reproducibility of the densification. In summary, the procedure included: (i) manual collection and cleaning to remove impurities (soil/sand and foreign materials), reducing the inorganic fraction and improving the response to compression (Kaliyan and Morey, 2009; Tumuluru et al., 2011); (ii) combined drying to control humidity, a critical variable of compactness and mechanical durability: solar drying for three consecutive days (≈10 h/day; 30–35 °C; RH ≤ 60%) and complementary drying in a convection oven (Memmert) at 35–60 °C for 180 min, until the material is standardized and the residual moisture is reduced to <10 % (Kaliyan and Morey, 2009; Serrano et al., 2011; ISO, 2023); (iii) particle size reduction and classification to optimize packing: primary crushing (<10 mm) with Oster blender (six blades, auger shaft), grinding in MS 300 mill and sieving (3 mm mesh) to obtain ≤3 mm fraction (Kaliyan and Morey, 2009; Tumuluru et al., 2011).

Gelatinized cassava starch was used as a binder, due to its ability to increase cohesion and densification resistance: 20 g of starch was dispersed in 60 mL of cold water and incorporated into 120 mL of boiling water until a colloidal paste was obtained, standardizing its rheological status (Aransiola et al., 2019; Gong et al., 2024; Kaliyan and Morey, 2010). Subsequently, the biomass was mixed with the binder until homogeneous operational plasticity was achieved, avoiding gradients of humidity and binder distribution that compromise mechanical integrity (Aransiola et al., 2019; Kaliyan and Morey, 2009). Forming was carried out by pressing in cylindrical molds calibrated with a hydraulic press, under controlled pressure, since densification depends on the pressure applied and the geometric stability of the product (Kaliyan and Morey, 2009; Tumuluru et al., 2011). The briquettes obtained had a mass of 50 g, a diameter of 70.68 mm, a length of 50 mm and an approximate density of 263.15 kg/m³. Finally, natural drying was applied on steel trays in a ventilated environment (28–32 °C, ~72 h) to constant mass, to stabilize humidity and ensure comparability of results (ISO, 2023).

Experimental design and treatment formulation (DCA)

A one-factor completely randomized design (CRD) was implemented. The experimental factor was the dry mass ratio of the internal matrix to the peripheral layer (MI:CP) of sugarcane bagasse (*Saccharum officinarum*), considering that pith-rich and fiber-rich fractions may differ in their contribution to briquette densification behavior and energy performance (Madlala et al., 2021). Four treatments were evaluated: T1 (25:75), T2 (50:50), T3 (75:25), and T4 as control (100:0; whole bagasse without fraction separation). In all treatments, formulation conditions were kept constant at 50 g of dry residue per experimental unit and 20% cassava starch binder (w/w relative to the dry biomass mass). Keeping the binder proportion constant allowed the specific effect of MI:CP composition to be isolated, since binders generally improve density and mechanical integrity but may also alter the calorific performance of briquettes when their heating value differs from that of the lignocellulosic material (Ezéchiel et al., 2022; Obi et al., 2022).

Each treatment had three independent replicates (n = 3), resulting in a total of 12 experimental units. Treatment allocation to the experimental units was performed by simple randomization. First, the 12 units were coded sequentially (U1–U12). Then, the four treatments were each repeated three times and assigned to these coded units using a random allocation procedure generated in Microsoft Excel with the RAND() function, followed by ranking of the random values in ascending order. This procedure ensured that each unit had the same probability of receiving any treatment and minimized allocation bias. The final distribution of treatments and the detailed composition of each experimental unit are presented in Table 2.

Energy performance of solid biofuel (briquettes)

The physicochemical and energetic characterization of the briquettes was carried out at the Biomass Laboratory of the IIGE (Institute of Geological and Energy Research (IIGE) in Quito-Ecuador applying standardized methods of proximal analysis for solid biofuels, in order to ensure comparability, reproducibility and metrological traceability.

All measurements were performed in triplicate (n = 3) for each treatment. Results are expressed as mean ± standard deviation (SD) (Table 4).

Calibration and quality assurance

The analyses were performed, specifically at the Biomass Laboratory of the Instituto de Investigación Geológico y Energético (IIGE). The images presented correspond to representative equipment used in biomass laboratories, which

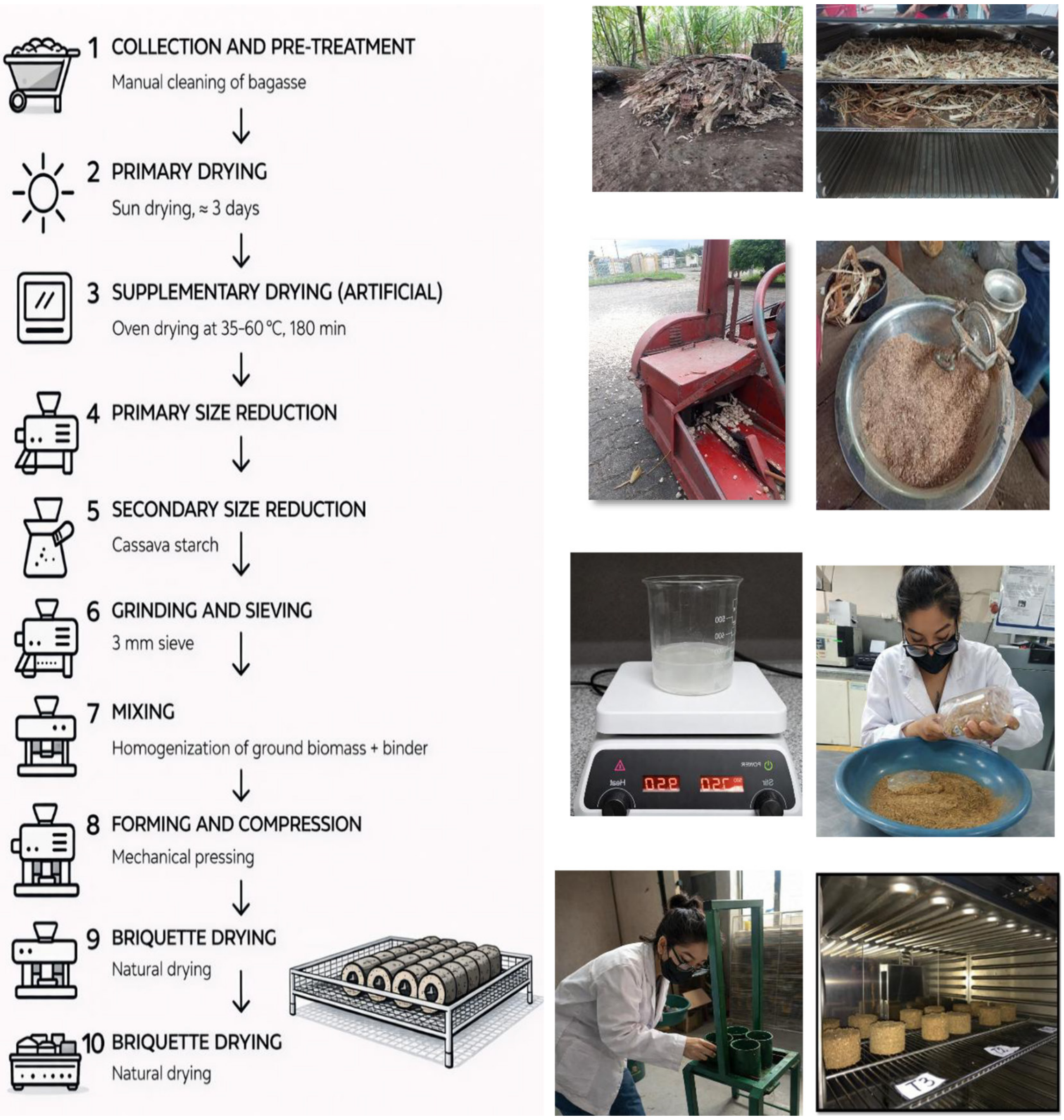

Figure 5. Solid biofuel processing (briquettes)

Table 2. Composition and randomized allocation of the experimental units

Experimental unit	Assigned treatment	Binder (%)	Dry bagasse mass (g)	Internal matrix (g)	Peripheral layer (g)	MI:CP ratio
U1	T2	20	50	25.0	25.0	50:50
U2	T4	20	50	50.0*	0.0*	100:0*
U3	T1	20	50	12.5	37.5	25:75
U4	T3	20	50	37.5	12.5	75:25
U5	T1	20	50	12.5	37.5	25:75
U6	T2	20	50	25.0	25.0	50:50
U7	T4	20	50	50.0*	0.0*	100:0*
U8	T3	20	50	37.5	12.5	75:25
U9	T2	20	50	25.0	25.0	50:50
U10	T1	20	50	12.5	37.5	25:75
U11	T3	20	50	37.5	12.5	75:25
U12	T4	20	50	50.0*	0.0*	100:0*

Table 3. Method analysis of physicochemical and energy parameters of the sugarcane bagasse by-product

Parameter	Method
Humidity	Gravimetric method by drying in an oven; ISO 18134-2:2024
Volatile matter	Gravimetric method for determination of volatile matter in dry sample, in a closed crucible and under standardized heating; UNE-EN ISO 18123:2024 / ISO 18123:2023
Ashes	Gravimetric method for the determination of ash by mineral waste after controlled incineration; UNE-EN ISO 18122:2023 / ISO 18122:2022
PCS (HHV)	Direct calorimetric method in calorimetric pump; UNE-EN ISO 18125:2018 / ISO 18125:2017

Table 4. Measurements performed in triplicate (n = 3)

Treatment	Moisture (%)	Volatile matter (% db)	Ash (% db)	HHV (MJ/kg db)
T1	8.93 ± 0.04	82.99 ± 0.21	2.30 ± 0.14	18.34 ± 0.07
T2	9.61 ± 0.08	82.15 ± 0.31	3.17 ± 0.06	18.01 ± 0.16
T3	9.18 ± 0.06	82.91 ± 0.24	2.65 ± 0.06	18.28 ± 0.08

operate under the same standardized principles defined by ISO methods. Furthermore, the Biomass Laboratory operates within an institutional quality framework aligned with the Servicio de Acreditación Ecuatoriano (SAE) and the ISO/IEC 17025 standard. All analytical equipment was calibrated and verified prior to and during the experimental campaign:

- analytical balance calibrated using certified reference weights (OIML class E2);
- oven and furnace temperatures verified using calibrated thermocouples (deviation < ±2 °C);
- bomb calorimeter calibrated using certified benzoic acid (~26.454 MJ/kg);
- repeatability was verified through replicate analyses, maintaining RSD < 2% for HHV and < 5% for proximate analysis.

Statistical analysis

The analysis was conducted under a completely randomized design (CRD) with four treatments and three independent replicates per treatment (n = 3). Statistical analyses were performed using IBM SPSS Statistics version 25.

Prior to inferential analysis, model assumptions were evaluated based on residuals, including normality using the Shapiro–Wilk test and homogeneity of variances using Levene's test (Midway et al., 2020; Zhou et al., 2023; Gosselin, 2024; Kamath et al., 2025). When assumptions were satisfied ($p > 0.05$), treatment means were compared using one-way ANOVA ($\alpha = 0.05$), followed by Tukey's Honestly Significant Difference (HSD) test for multiple pairwise comparisons while controlling the family-wise error rate (Agbangba et al., 2024; Gurski and Dittel, 2026).

In cases of heteroscedasticity ($p < 0.05$), a Welch ANOVA was applied as a robust alternative, followed by Games–Howell post hoc comparisons, which do not assume equal variances (Zhou et al., 2023; Gurski and Dittel, 2026). All results are expressed as mean ± standard deviation.

RESULTS

Generation of sugarcane bagasse in artisanal production – brandy SMEs (*Saccharum officinarum*)

The process begins with the reception, weighing and batching of the cane, followed by selection and cleaning to remove foreign material (and, when applicable, generate a washing effluent with solids) (Figure 6). The sugarcane is chopped and fed to the sugar mill, where the milling/extraction separates two streams: raw juice and bagasse (a fibrous by-product with moisture and residual sugars), whose collection and handling condition its energy or agronomic recovery. The juice is screened/filtered and, according to local practice, clarified and pH controlled (e.g. liming), at which stage sludge/cachaça can be generated. Subsequently, °Brix and pH of the must are adjusted for a controlled fermentation, which produces the alcoholic broth and releases CO_2. Finally, distillation allows the heads, heart and tails to be separated to ensure the quality of the brandy, generating the vinasse as the main residual stream, before packaging and storage under hygienic and quality control conditions.

Figure 6. Production process of brandy from sugar cane (*Saccharum officinarum*) in small and medium-sized enterprises

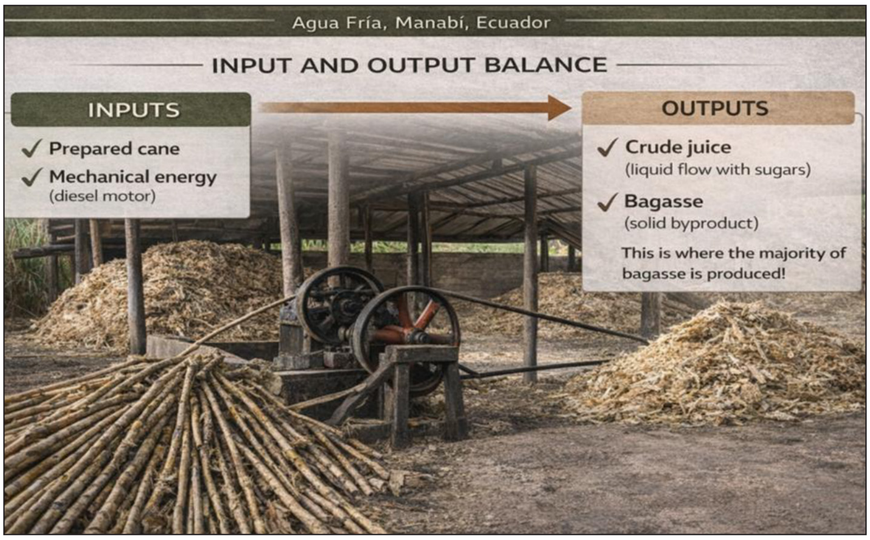

Figure 7. Grinding/extraction of cane in artisanal sugar mills (Agua Fría, Manabí, Ecuador)

Balance of inputs and outputs and generation of sugarcane bagasse (*Saccharum officinarum*) in the production of sugarcane spirits

Milling is the point of generation of bagasse, a fibrous by-product resulting from the solid-liquid separation of the stem; Its production occurs before the conditioning of the juice and fermentation, so its management (collection, drying and destination) must be defined in the extraction stage (Figure 7).

Grinding/extraction performance (1 pass) and mass balance

Table 5 illustrates the mechanical separation in the artisanal sugar mill: from the entered sugarcane, two dominant currents are generated, wet bagasse (fibrous solid) and raw juice (liquid). The bagasse/cane yield varies between 34.31–44.00%, reflecting the sensitivity of the process to typical conditions of artisanal milling (roller adjustment/

Table 5. Bagasse generation performance (grinding – 1 pass; wet bagasse)

Essay	Processed cane (kg)	Wet bagasse (kg)	Estimated Juice (kg)	Bagasse/Sugarcane (%)
1	10.20	3.50	6.70	34.31
2	22.50	9.10	13.40	40.44
3	40.00	17.60	22.40	44.00
Total	72.70	30.20	42.50	

compression, feeding speed, cane condition and moisture). In practical terms, here is the point you want to emphasize: the largest generation of bagasse is concentrated in the milling/extraction phase, so this stage is the most important nodule to quantify waste and propose its use (Briquettes as solid fuel).

Table 6. It illustrates that an overall factor of 0.4154 kg/kg means that, for every 1 kg of cane processed, 0.415 kg of wet bagasse is generated on average. This parameter is key to directly determining that the milling generates the bagasse sufficiently for recovery (briquetting).

Table 7 projects that the projection allows the global generation factor to be translated into operational-scale scenarios, which are especially useful in the discussion on the applicability and feasibility of bagasse use. In this context, the estimated value of 415 kg of wet bagasse per ton of processed sugarcane constitutes a key indicator of biomass availability, by linking the measurement obtained in the field with the real supply potential of the system.

From the perspective of the process chain, this relationship allows the point of generation of the waste to be articulated with its energy use, evidencing that, under conditions of continuity in milling, the flow of bagasse could predictably support the implementation of subsequent stages of drying and briquetting.

Proximal characterization, by-product sugarcane bagasse (*Saccharum officinarum*)

Table 8 of the behavior observed during the 12 days of monitoring confirms that the bagasse generated presented high moisture levels (46–56% bh), a condition that defines a relevant operational restriction for its use as solid biofuel. On the other hand, the high volatile matter and low temporal variation suggest that the combustible organic fraction of the bagasse maintained a relatively uniform composition, which is a favorable characteristic from the perspective of its thermochemical behavior. This relative stability strengthens the suitability of the waste for combustion processes, by indicating a more predictable energy response within the evaluated period. On the other hand, the ash content showed variation, indicating that the mineral fraction of the material was more exposed to alterations derived from post-harvest handling and operating conditions. Table 9 illustrates that the humidity is moderately dispersed (CV ~7%), indicating that the bagasse comes out wet persistently, so drying should be considered part of the process if briquetting is intended; the volatile matter is highly homogeneous (CV <2%), reinforcing that the organic fraction of the bagasse is consistent and favorable for combustion; and ash shows the greatest variability (CV ~23%), which technically suggests that the improvement in quality is not only about drying, but also about reducing inert carryover (improvements in cleaning/selection/stockpiling).

Table 7. Final bagasse generation model (scaling)

Scale	Processed cane	Bagasse generated (kg)
Per 1 kg	1 kg	0.415
Per 100 kg	100 kg	41.5
Per 1 ton	1000 kg	415
Sample Lot	40 kg	16.6

Table 6. Indirect calculations – Global bagasse generation factor

Parameter	Applied formula	Result
Global bagasse/sugarcane factor (wet)	30.20 / 72.70	0.4154 kg/kg
Percentage generation	0.4154 × 100	41.54%
Juice/cane (by difference)	1−0.4154	0.5846 kg/kg
Percentage juice	0.5846 × 100	58.46%

Table 8. Proximal characterization of sugarcane bagasse bagasse (*Saccharum officinarum*)

Sample	Humidity (% bh)	Volatile matter (% bs)	Ashes (% bs)
M01	52.39	86.24	2.88
M02	48.23	81.96	5.16
M03	54.92	85.31	3.08
M04	46.30	84.47	3.50
M05	46.27	83.81	3.44
M06	51.45	84.05	3.51
M07	54.09	83.65	2.82
M08	52.98	85.83	3.89
M09	55.57	86.16	3.88
M10	46.97	81.97	5.51
M11	54.07	82.68	5.14
M12	55.73	83.73	4.01

Table 9. Statistics (n = 12) of proximal characterization

Variable	Average ± OF	Range (min–max)	CV (%)
Humidity (% bh)	51.58 ± 3.67	46.27–55.73	7.11
Volatile matter (% bs)	84.16 ± 1.51	81.96–86.24	1.79
Ashes (% bs)	3.90 ± 0.91	2.82–5.51	23.35
Fixed carbon (% bs)	11.94 ± 1.08	9.96–13.53	9.01

Physicochemical and energy characterization of briquettes

The results obtained in Table 10 show briquettes with low residual moisture (8.89–9.69%), a characteristic that confirms adequate conditions for conditioning the material for use as solid biofuel. This behavior is technically favorable, since it contributes to improving the stability of the product during storage, reduces susceptibility to deterioration and optimizes its energy performance by minimizing the non-useful energy associated with water evaporation.

Likewise, volatile matter on a dry basis remained at high levels (81.83–83.23%), which evidences the predominance of combustible organic compounds and suggests a favorable thermochemical response during ignition and combustion. This condition reinforces the energetic aptitude of the briquettes, as they are associated with a dominant and relatively homogeneous fuel fraction between treatments.

The main differentiation between matrices was observed in the ash content (2.14–3.22%), indicating variations in the mineral load of the

Table 10. Characterization of briquettes

Test matrix	Humidity (%)	Volatile matter (% w/w bs)	Ash (% w/w bs)	Higher caloric value (MJ/kg bs)
S1R1	8.96	83.23	2.42	18.26
S1R2	8.93	82.88	2.14	18.40
S1R3	8.89	82.87	2.34	18.36
T2R1	9.62	82.16	3.10	18.19
T2R2	9.53	81.83	3.19	17.91
T2R3	9.69	82.45	3.22	17.93
S3R1	9.22	82.85	2.64	18.35
T3R2	9.22	83.18	2.71	18.31
S3R3	9.11	82.71	2.59	18.19

densified material. This variation is relevant because the inorganic fraction not only proportionally reduces the fuel content, but can also affect the thermal efficiency of the biofuel and increase the generation of waste during its use. Accordingly, the PCS was located in a narrow range (17.91–18.40 MJ/kg bs), although with slightly lower values in the matrices with a higher proportion of ash, a pattern consistent with the relative reduction of energetically active organic matter.

Statistical analysis

After the comparison between treatments, the assumptions of the model were verified: normality of residuals using Shapiro–Wilk and homogeneity of variances using Levene (median-centered). Since the assumptions were considered acceptable in all variables ($p \geq 0.05$), a one-way ANOVA was applied for each response ($\alpha = 0.05$). When the overall contrast was significant, the differences between pairs were identified with Tukey HSD, controlling for family error. To quantify the practical magnitude of the treatment effect, η^2 and ω^2 were reported.

The results in Table 11 show that, for all the variables evaluated, the assumptions of normality and homogeneity of variances were met, since the values of Shapiro-Wilk and Levene were greater than 0.05. This indicates that the data are suitable for the ANOVA application. Statistically significant differences were observed in all the variables analyzed, demonstrating that the formulation of the briquettes significantly influenced their physicochemical and energetic properties.

Multiple comparisons (Tukey HSD, α = 0.05)

Tukey's post hoc analysis of HSD ($\alpha = 0.05$) showed that the response of the treatments was not homogeneous among the variables evaluated. In moisture and ash, a complete discrimination between treatments was verified, following the gradient T2 > T3 > T1, while in volatile matter and higher calorific value (PCS) the differentiation was partial, so that T1 and T3 did not differ statistically from each other, but both exceeded T2.

From the integral perspective of biofuel quality, these results show T2 as the treatment with higher humidity, higher ash content and lower GWP, therefore, it is not better not to use it. Although T1 and T3 achieved statistically equivalent values of PCS, the superiority of T1 is sustained by incorporating complementary operational criteria. In fact, T1 simultaneously presented the lowest humidity and the lowest ash content, attributes that favor the stability of the fuel, reduce the inert load and improve its potential performance during combustion. Consequently, T1 can be considered the treatment with the best overall performance, as it combines high energy quality with better physicochemical characteristics for its valorization as biofuel.

DISCUSSION

The identification of milling/extraction as a critical step in bagasse generation clearly situates the point in the process at which the primary separation between the fermentable liquid fraction and the lignocellulosic residue is defined. This precision is not merely descriptive, because the juice yield, the amount of bagasse produced and its initial physical attributes depend simultaneously on this operation. In terms of process, this node allows the origin of the by-product to be interpreted from a functional logic and not just a sequential one. In fact, as Corbion et al. (2023) and Ratkovich et al. (2023) point out, the control achieved in the early stages of extraction decisively conditions the quality of subsequent streams in systems based on sugarcane juice.

From this, bagasse should be read as a coproduct whose potential value emerges from the process architecture itself, aligning with what was reported by Ajala et al. (2021) and Hiranobe et al. (2024), who highlight the growing relevance of sugarcane lignocellulosic residues in bioenergy,

Table 11. Assumptions, ANOVA of the physical, chemical and energy parameters of briquettes

Variable	Shapiro (p)	Levene (p)	ANOVA (p)
Humidity (%)	0.4489	0.7489	<0.001
Volatile matter (% bs)	0.3790	0.8467	0.0123
Ashes (% bs)	0.8322	0.5642	<0.001
PCS (MJ/kg bs)	0.1864	0.8157	0.0222

materials, and biorefinery routes. From this perspective, the flowchart represents the artisanal process that allows us to operationally locate the point at which the opportunity for valorization begins and, at the same time, the moment at which quality losses associated with moisture, compaction or the incorporation of inerts may occur.

Accordingly, the variation in bagasse/sugarcane yield between 34.31 and 44.00% shows the sensitivity of the artisanal system to relatively subtle changes in the milling operation, this interval suggests the concurrence of factors linked to both the raw material and the mechanical performance of the mill, including the physiological state of the sugarcane, the pressure exerted by the mill and the number of passes applied during extraction. In freshly harvested bagasse, Ajala et al. (2021) and Hiranobe et al. (2024) show that the moisture content and remaining sugars are closely dependent on how efficiently the separation between juice and fibre occurs. Consequently, a higher yield of wet bagasse should not be automatically interpreted as an advantage, but may reveal a less efficient recovery of the liquid fraction.

This same logic gives special relevance to the global factor of 0.4154 kg/kg, since it transforms a spot observation of the field into a coefficient with operational utility for the management of SMEs. Its value lies not only in quantifying the relationship between processed sugarcane and bagasse generated, but also in offering a basis for projecting biomass availability, sizing storage areas and anticipating drying requirements before briquetting. In artisanal systems, where process variability often limits planning, this type of coefficient allows empirical dynamics to be translated into a technical management criterion. In this sense, Kpalo et al. (2020) and Tumuluru et al. (2011) emphasize that the viability of densification depends not only on the intrinsic quality of the material, but also on the predictability of the flow with which it is generated and incorporated into the transformation process.

The scaling up to 415 kg of wet bagasse per ton of processed sugarcane reinforces the argument of local availability of biomass and provides concrete support for an eventual recovery route within the production unit itself. The bagasse, therefore, does not correspond to a sporadic flow, but to a residual stream with a sufficient volume to justify a planned management strategy. This point is especially important from the environmental point of view, since the direct disposal or burning of a waste of this magnitude implies avoidable costs and externalities. According to the Commission for Environmental Cooperation (2014) and Matsueda and Antunes (2024), the reincorporation of agro-industrial waste into circular economy and energy substitution schemes represents a concrete way to reduce environmental liabilities and, simultaneously, generate value at local production scales.

However, the possibility of recovery depends not only on the volume available, but also on the initial quality of the material. In this study, the high humidity of fresh bagasse (46.27–55.73% bh) confirms that the residue leaves the mill under conditions that are unfavorable for immediate densification. This behavior is consistent with what has been described for sugarcane waste, in which the water retained in the fibrous matrix compromises the stability of the material, increases the energy demand of drying and reduces the thermal performance when the biomass is used without prior conditioning. In this regard, Ajala et al. (2021) and Mekonen et al. (2024) agree that high initial humidity is one of the main constraints for the direct energy use of bagasse. Thus, the incorporation of a drying step prior to the forming of briquettes does not appear as an accessory decision, but as a methodological requirement derived from the nature of the material itself.

From the proximal composition, the high and relatively homogeneous volatile matter, together with a fixed carbon close to 12% bs, suggests that the bagasse retains an organic fraction favorable for combustion, with a relatively rapid ignition and a complementary contribution of ember during burning. This condition is characteristic of lignocellulosic biomasses with energy potential and helps explain why sugarcane bagasse has historically been considered a promising raw material. However, a rigorous energy reading cannot be exhausted in the fuel fraction. As emphasized by Racero-Galaraga et al. (2024) and Vassilev et al. (2017), the mineral fraction conditions the remaining residue, the cleanliness of the system and the overall combustion efficiency, so the energy suitability of bagasse must be discussed from an integrated view of its organic and inorganic components.

Precisely, the greater variability observed in ash content suggests that the quality of bagasse is not determined exclusively by sugarcane as a raw material, but also by post-harvest handling and storage conditions. The fluctuating presence of inerts may be associated with contamination with soil, sand, or other impurities incorporated during transport, storage, or handling prior to drying. This observation has direct technical implications, because it indicates that an improvement strategy in SMEs should not be limited to reducing humidity, but also to restricting the entry of mineral pollutants. Hiranobe et al. (2024) and Wani et al. (2023) warn, indeed, that these inert fractions have a negative impact on the final quality of densified biofuel. Therefore, the improvement of bagasse as an energy resource begins both in its conditioning and in its physical preservation from the moment of generation.

Once the conditioning was applied, the briquettes obtained had a final humidity between 8.89 and 9.69%, a technically favorable range for storage and energy use. This behavior is consistent with densification, in which moderate moisture contents are associated with better compactability, lower risk of cracking and greater stability of the final product. Kaliyan and Morey (2009) and Kpalo et al. (2020) agree that humidity control is a critical variable to ensure acceptable physical performance during handling and combustion. Consequently, the conditioning applied in this study was effective, not only because it reduced the humidity of an initially very wet biomass, but also because it generated comparable conditions to evaluate the technological response of the treatments formulated.

Consistent with this, the range of PCS obtained (17.91–18.40 MJ/kg bs) and the ash contents between 2.14 and 3.22% indicate that the briquettes produced achieved a competitive performance for a densified residual biomass at an experimental scale. These values support the viability of sugarcane bagasse as a solid fuel for local thermal applications, particularly when drying, particle size, and binder formulation directly modulate these indicators. Mekonen et al. (2024) and Suttibak et al. (2024) specify this sensitivity. Likewise, the inverse trend observed between ash and PCS is technically consistent, since an increase in the mineral fraction implies a proportional dilution of the fuel fraction and, therefore, a penalty of the energy value of the material.

At the comprehensive level of the treatments, T1 showed the best overall performance by combining the lowest moisture and ash content with a PCS statistically equivalent to that of T3 and higher than that of T2. This selection does not respond only to a numerical comparison of averages, but also to a functional logic of biofuel quality. Indeed, Aransiola et al. (2019) and Tumuluru et al. (2011) argue that the evaluation of densified fuels must jointly consider energy indicators and operational attributes, since a material is not defined only by its calorific value, but also by the inert charge it introduces and by its stability during storage, handling, and combustion. Under that criterion, the T1 advantage becomes technically more consistent than a selection based solely on maximizing PCS.

The significance observed in the ANOVA for the four variables evaluated, which confirms that the MI:CP composition influenced the quality of the solid biofuel, demonstrating that modifications in the composition of the material translate into differentiated technological responses during densification. In this context, discrimination specified which treatments were separated from each other, Agbangba et al. (2024) and Midway et al. (2020), who highlight the importance of complementing the global evidence of ANOVA with multiple comparisons that allow a more exhaustive interpretation of treatments. Within this framework, the most marked contrasts in moisture and ash are particularly relevant, since both variables are among the most sensitive descriptors of quality in briquettes and pellets. Their technical importance lies in the fact that they directly affect combustion efficiency, the amount of inert fraction remaining and the behavior of the material during storage and handling. Consequently, statistical evidence not only confirms differences between treatments, but also guides the selection criteria towards the attributes with the highest functional incidence. This coincides with Kaliyan and Morey (2009) and Vassilev et al. (2017), for whom moisture and ash reduction is a central condition for improving the energy and operational performance of densified solid fuels.

Finally, although volatile matter and PCS also showed significant differences, the separation between treatments was more moderate, suggesting that these indicators respond to less linear compositional and process interactions. From this perspective, the convergence between inferential evidence and operational criteria supports the choice of T1 as the preferred treatment. However, Gurski and Dittel (2026) and Zhou et al. (2023) suggest further strengthening the stability of this inference and macro scales.

CONCLUSIONS

This study provides clear empirical evidence that artisanal sugarcane milling/extraction is the decisive stage for bagasse generation in small-scale brandy production, producing a consistent and substantial residual biomass quantified at 0.415 kg of wet bagasse per kg of processed cane (41.54%). This finding establishes a reliable basis for planning energy recovery and valorization strategies within agro-industrial SMEs.

The proximal characterization of bagasse revealed high initial moisture, high volatile matter, and variable ash content, highlighting the necessity of pre-conditioning. Controlled drying and removal of impurities were identified as critical steps to transform raw bagasse into a stable and high-quality solid biofuel.

The densification process successfully produced briquettes with low final moisture, reduced ash content, and competitive higher calorific value (17.91–18.40 MJ/kg), demonstrating the technical feasibility of using sugarcane bagasse as a solid fuel in artisanal settings. Among the treatments tested, T1 achieved the optimal combination of physicochemical and energetic properties, confirming that tailored processing significantly enhances fuel quality.

Overall, the study validates the hypothesis that controlled processing of sugarcane bagasse improves its energy content and physicochemical stability, providing a robust and replicable framework for the local valorization of agro-industrial residues. This work contributes a novel, quantifiable link between feedstock generation, conditioning, and densified fuel performance, offering a scientific basis for sustainable bioenergy implementation in small-scale enterprises.

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