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Lignocellulosic Feedstock Evaluation (Sugarcane Bagasse and Coconut Shells) for Ethanol Production as a Potential Refinery Fuel Additive

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Abstract: This study evaluated the potential of sugarcane bagasse and coconut shells as feedstocks for producing second-generation ethanol intended as a sustainable oxygenate additive in refinery gasoline. Using a rigorous methodology that included physicochemical characterization of the biomass, acid hydrolysis and fermentation with *Saccharomyces cerevisiae*, and robust statistical analysis, the results demonstrated the technical feasibility of both residues. Coconut shells stood out for their higher calorific value (16.44 MJ/kg) and significantly higher fermentation yield (90.42%) compared to bagasse (12.6 MJ/kg and 83.20%). Both ethanol products had alcohol contents above 93% v/v, complete combustion with no detectable residues, and, critically, extremely low sulfur content (<0.12%). Statistical analysis using Student's t-test for independent samples ($\alpha = 0.05$) confirmed a significant difference in fermentation yields between the two biomasses ($p = 0.012$). However, the low final ethanol titers (≈6 g/L) obtained under the current non-optimized protocol remain a critical bottleneck. It is concluded that while both residues are technically feasible as feedstocks, substantial process optimization, particularly in pretreatment and hydrolysis, is required before their ethanol can be considered for industrial application. The extremely low sulfur content (<0.12%) supports their potential for producing cleaner fuels within a circular economic framework. Recovering these wastes through co-processing in refineries is an effective strategy to promote the circular economy, improve fossil fuel quality (by increasing octane ratings), and contribute to the decarbonization of the transport sector.

Keywords: Potential; Lignocellulosic waste; Sugarcane bagasse; Coconut shells; Refining additives.

1. Introduction

Biomass is defined as organic matter that contains oxygen atoms in its chemical composition, unlike fossil fuels. The presence of this atom means that biomass requires less oxygen from the air, making it less polluting; however, the amount of energy released is reduced, thereby lowering its higher heating value. Lignocellulosic biomass refers to plant-based material primarily composed of hemicellulose (20-35%), lignin (5-30%), and cellulose (35-50%) (Cardoso et al, 2023). In general, the literature defines biomass as all non-fossil organic material that can be converted into energy, meaning it contains chemical energy. This includes all aquatic and terrestrial vegetation, trees, virgin biomass, organic waste, agricultural residues, animal manure, and other industrial waste.

Society is currently challenged by reconciling the growing demand for energy with the undeniable need for sustainability. The progressive depletion of fossil fuels and rising greenhouse gas emissions motivate the use of renewable, sustainable, and low-cost energy sources. In this context, second-generation ethanol has been identified as an alternative to petroleum-derived fuels because it is derived from lignocellulosic biomass. This biomass is renewable, geographically well distributed, environmentally favorable for CO_2 sequestration, does not compete with agriculture for human food production, and is abundant and low-cost. The effective application of lignocellulosic materials requires pretreatment stages that promote the fractionation of their main constituents (cellulose, hemicellulose, and lignin) (Ortiz et al., 2014a, 2014b).

The combination of different pretreatments is explored to increase sugar-recovery and minimize the release of substances that may inhibit microbial metabolism, thereby affecting fermentation efficiency and productivity.A promising alternative is to use a dilute alkaline pretreatment before an acid pretreatment, thereby producing a hemicellulosic hydrolysate richin xylose and low in inhibitory compounds, as well as a solid rich in cellulose that is more susceptible to enzymatic action. Enzymatic saccharification and fermentation can be performed simultaneously (SSF) or separately (SHF). The first configuration is favorable, as it reduces the inhibitory effect of glucose on the enzymatic complex, since glucose is continuously converted to ethanol by yeasts (Santiago et al., 2017).

Dilute acid pretreatment in lignocellulosic ethanol production generates inhibitors such as furfural, HMF, and acetic acid (Pandey, Kaur and Gaur, 2025), which reduce ethanol productivity by up to 80%, with a toxicity order of furfural > HMF > formic acid > acetic acid ≈ levulinic acid (Jung & Kim, 2017). Furthermore, the presence of residual lignin and pseudo-lignin (formed from HMF and furfural under acidic, high-temperature conditions) hinders enzymatic hydrolysis by adsorbing cellulases and blocking substrate access (Xu et al., 2025; Liu et al., 2025; Chen et al., 2024; Hua et al., 2024). To overcome these challenges, strategies such as the development of tolerant microbial strains (Du et al., 2025; 2024), detoxification methods including nanoparticles (2025), and the use of hydrophobically modified copolymers or mixed surfactants (Xu et al., 2025; Liu et al., 2025) have been explored. Multi-omics approaches, integrated with artificial intelligence, are being applied to elucidate cellular stress-response pathways and to guide precision strain engineering toward industrial process viability (Pandey, Kaur and Gaur, 2025).

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Considering this, the present study aimed to evaluate the technical potential of sugarcane bagasse and coconut shells as feedstocks for producing second-generation ethanol intended as an oxygenated additive in refinery gasoline. Specifically, the objectives were:

i. To produce ethanol from both biomasses via dilute acid pretreatment, enzymatic hydrolysis, and fermentation with *Saccharomyces cerevisiae*.
ii. To characterize the physicochemical properties of the resulting biofuels (alcohol content, density, calorific value, elemental composition).
iii. To compare the fermentation yields and energy potentials using statistical analysis (t-test, $\alpha = 0.05$).
iv. To identify critical bottlenecks limiting immediate application as a refinery additive.

The following hypothesis was tested: **H_1:** Coconut shells, due to their lower moisture content and higher lignin fraction, will yield ethanol with significantly higher fermentation efficiency (>5% absolute) and superior energy density (higher calorific value) compared to sugarcane bagasse, under identical pretreatment and fermentation conditions.

Although several studies have evaluated lignocellulosic biomass for second-generation ethanol production, limited research has compared sugarcane bagasse and coconut shell under identical pretreatment and fermentation conditions for potential use as additives in refinery systems, particularly in African contexts.

1.1. Previous Studies

1.1.1. Lignocellulosic biomass

Lignocellulosic materials are an alternative to fossil fuels, since sugary materials are currently used as feedstock for ethanol production (e.g., sugarcane juice). These materials are considered advantageous because they are renewable, environmentally friendly, do not compete with agriculture for human or animal food, and are abundant and low-cost. Lignocellulosic material is mainly composed of an aromatic structure called cellulose, hemicellulose, and lignin. Figure 1 presents a schematic representation of the structure of lignocellulosic biomass, highlighting the spatial arrangement and interactions among its main components.

The illustration depicts cellulose microfibrils embedded in a hemicellulose matrix, with lignin serving as an outer binder that imparts rigidity and recalcitrance. This structural complexity is central to understanding why lignocellulosic biomass cannot be directly fermented into ethanol without pretreatment.

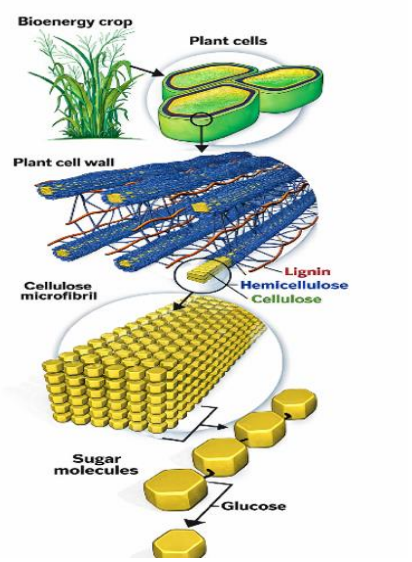


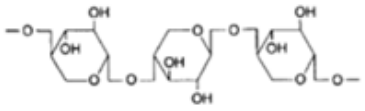
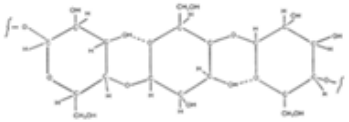
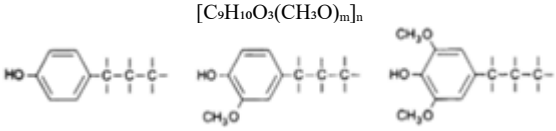
Figure 1: Lignocellulose biomass structure
Source: Adapted from Wyaman et al. (2009)

The Figure visually supports the text's discussion of cellulose crystallinity and lignin's protective role, reinforcing the necessity of pretreatment steps, such as the dilute acid hydrolysis employed in this study, to disrupt the lignocellulosic matrix and expose cellulose for enzymatic saccharification. Lignocellulosic material can be used to produce alcohol or biodiesel, which can serve as additives in various processes in traditional refineries. This, in turn, does not conflict with the food chain and is environmentally healthy.

1.1.2. Main characteristics of lignocellulosic biomass

The characteristics of lignocellulosic biomass make it a renewable resource with the potential to meet high global energy demand and reduce dependence on fossil fuels. Therefore, it is necessary to evaluate the physicochemical properties and composition of the products resulting from the various processes used to convert them into energy to ensure their quality for use as biofuels. Based on Basu (2010), the following Table shows the main constituents of lignocellulosic biomass and their molecular characteristics. Table 1 presents the main constituents of lignocellulosic biomass and their molecular characteristics.

Table 1: Main constituents of lignocellulosic biomass and their molecular characteristics

Component	Features	Molecular structure
Hemicellulose	Short-chain polymer composed of carbohydrates, forming a random and amorphous structure. It is one of the constituents of the cell wall of biomass.	$(C_5H_8O_4)_n$ 
Cellulose	Long-chain polymer consisting of thousands of d-glucose units that form a crystalline structure. It provides structural strength to biomass.	$(C_6H_{10}O_5)_n$ 
Lignin	A complex, three-dimensional branched polymer consisting mainly of phenylpropane units. Responsible for the cohesion and rigidity of biomass cells.	$[C_9H_{10}O_3(CH_3O)_m]_n$ 

Source: Basu (2010)

Table 1 represents the characteristics of the main components of lignocellulosic biomass. It explains, in simple terms, the properties of lignocellulosic fibers and the structure and function of the cell wall.

Cellulose is a polymer ($C_6H_{10}O_5$) with a long-chain structure composed of single glucose units; it is classified as a polysaccharide, a type of carbohydrate. Hemicellulose, on the other hand, is characterized by not having an ordered crystalline structure, i.e., it is amorphous. Lignin contains carbon, hydrogen, and oxygen in its composition, meaning that, in general, it is formed by three phenylpropanoid alcohols ($C_9H_{10}O_2$, $C_{10}H_{12}O_3$, $C_{11}H_{14}O_4$).

1.2. Potential of biomass for use as raw material for refineries

The use of biomass in refineries occurs mainly in two ways: co-processing, the integration of biomass streams with fossil streams in conven-

tional units, and dedicated biorefineries, which exclusively convert biomass into a wide range of bioproducts (Al-Sahhaf et al., 2011). While traditional refineries transform oil into fuels and chemicals, biorefineries use biomass as a raw material to produce bioenergy, food, feed, materials, and essential chemicals.

According to Aguiar et al. (2020), the increase in advanced biofuel production, driven by global regulations, may lead to idleness in existing processing units. This creates a favorable scenario for integrating fossil and biomass streams, enabling their co-processing in existing units. In times of economic hardship, installing co-processing units in existing refining schemes is one of the most viable ways to facilitate the transition. Lignocellulosic biomass can be converted into "green carbon" products such as ethanol, butanol, biodiesel, and aviation kerosene (QAV) (Barros et al., 2025).

Due to its low nutritional value as animal feed and high energy potential, Angola grass (Brachiaria purpurascens) was experimentally converted into ethanol with a purity of 94.6% (v/v), demonstrating its viability as a biofuel feedstock (Morais et al., 2022a). Subsequently, the ethanol obtained was evaluated as an oxygenated additive in Straight Run gasoline produced at the Luanda Refinery, resulting in significant improvements in octane rating, with increases of 91% for light gasoline and 81% for heavy gasoline (Morais et al., 2022b).

1.2.1. Potential of sugarcane bagasse

Sugarcane (Saccharum officinarum L.) is a grass of the Poaceae family, whose processing generates bagasse (about 280 kg per ton of crushed cane) as its main residue (Silva, 2015). Although part of this bagasse is burned to generate energy in mills, a significant surplus (40-50 kg/ton) becomes an environmental liability.

Currently, bagasse is the subject of studies on its energy potential for biofuel production, notably cellulosic ethanol (2G). Its use for this purpose would significantly increase national biofuel production without expanding cultivated areas (Silva, 2015). Figure 2 summarizes the four primary objectives of pretreatment: increasing surface area, separating the lignin-cellulose complex, reducing cellulose crystallinity, and minimizing inhibitor formation.

These objectives guided the study's choice of dilute acid pretreatment. The Figure emphasizes pretreatment as a critical determinant of hydrolysis efficiency and fermentation yield. Chemically, bagasse is mainly composed of cellulose, hemicellulose, and lignin. Its composition varies depending on soil type, sugarcane variety, and management techniques (Silva, 2015). To efficiently convert this biomass into ethanol, pretreatment is essential to increase the exposure of cellulose fibers to hydrolytic enzymes. This is a critical phase for the overall cost and efficiency of the process. (Silva, 2015).

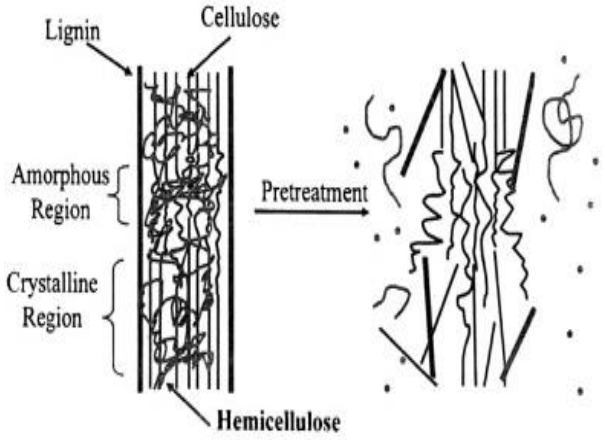


Figure 2: Objectives of pretreating a lignocellulosic material
Source: HSU et al. (1890)

The Figure illustrates the main goals of pretreatment: increasing surface area, separating the lignin-cellulose complex, reducing cellulose crystallinity, and minimizing inhibitor formation. The objectives of pretreatment are to increase the surface area of the biomass, separate the lignin-cellulose complex, decrease the degree of crystallinity of the cellulose, and minimize the formation of inhibitory compounds in subsequent stages of hydrolysis and fermentation (Silva, 2015).

1.2.2. Potential of coconut shell

Coconut (Cocos nucifera L.) is a tropical crop of great socioeconomic importance. Increased consumption of coconut water generates a large volume of husks, which account for 80% to 85% of the fruit's weight and decompose slowly (up to 8 years), leading to environmental impacts in landfills (Cabral, 2015).

The husk consists of a fraction of fibers (coir) and another of powder. It is a lignocellulosic material with a high lignin content, which gives it hardness and durability (Cabral, 2015). Like sugarcane bagasse, Coconut shell has potential for producing 2G ethanol, making it an alternative for recovering this waste.

1.2.3. Production of ethanol as an additive for refineries

The predominant technology for converting biomass into ethanol is fermentation followed by distillation (Al-Sahhaf et al., 2011). Ethanol (ethyl alcohol) is a widely used biofuel, especially in Brazil, where it is sold in hydrated form (for flex-fuel engines) or anhydrous form (added to gasoline at 20%-25% by volume).

The flowchart illustrates the main stages of ethanol production from biomass: grinding, hydrolysis (to release sugars), fermentation, and distillation. As a gasoline additive, ethanol raises the octane rating of the mixture, improving engine performance and reducing emissions. However, it is crucial to respect the proportions recommended by vehicle manufacturers to avoid damage. The Table compares key properties, including octane number, calorific value, and density, highlighting the advantages of ethanol as an oxygenated, renewable additive.

Table 2: Comparison of the properties of ethanol and gasoline

Fuel properties	Ethanol	Gasoline
Chemical formula	C_2H_5OH	C_8H_{15}
Molecular weight (kg/kmol)	46	111
Octane number (RON)	109	97
Octane number (MON)	92	86
Cetane number	11	8
Reid vapor pressure (kPa) a 15 °C	16,5	75
Specific mass (kg/l) a 15 °C	0,8	0,75
Lower calorific value (MJ/kg) a 15 °C	26,4	41,3
Lower calorific value (MJ/l) a 15 °C	21,2	31
Stoichiometric air/fuel ratio (kg air/kg fuel)	9	14,7
Boiling point (°C)	78	30-190

Source: Al-Sahhaf et al. (2011)

Ethanol is one of the most widely used renewable fuel additives worldwide due to its high-octane rating, oxygen content, and compatibility with existing gasoline infrastructure (Al-Sahhaf et al., 2011). As an oxygenated compound, ethanol can improve combustion efficiency and reduce pollutant emissions when blended with gasoline. Table 2 summarizes the main physicochemical properties of ethanol and gasoline relevant to fuel applications. Ethanol exhibits a higher research octane number (109) than gasoline (97), making it an effective octane enhancer. Although its lower heating value (26.4 MJ kg^{-1}) is lower than that of gasoline (41.3 MJ kg^{-1}), its renewable origin and environmental benefits support its use as a sustainable fuel component. In addition, ethanol has a lower Reid vapor pressure, which may contribute to reduced evaporative emissions under appropriate blending conditions. These characteristics justify its consideration as a potential renewable additive in refinery fuel formulations. Sugarcane bagasse and coconut shells are abundant lignocellulosic residues with significant potential for valorization through second-generation ethanol production. Their conversion into bioethanol may provide an alternative route for integrating renewable carbon into refinery systems, either through co-processing strategies or future biorefinery schemes. Consequently, the utilization of these residues contributes simultaneously to waste valorization, greenhouse gas mitigation, and the diversification of sustainable fuel sources.

2. Methodology

The present study evaluated sugarcane bagasse and Coconut shells as lignocellulosic feedstocks for second-generation ethanol production, with potential application as oxygenated additives in refinery gasoline. The experimental design followed a structured biorefinery approach comprising biomass preparation, physicochemical characterization, chemical and enzymatic conversion, fermentation, ethanol recovery, and statistical analysis.

Figure 3 presents the lignocellulosic biomasses investigated, namely sugarcane bagasse and Coconut shells. All experimental procedures, includ-

ing reducing sugar determination via the DNS method and ethanol quantification via distillation, were performed in biological triplicate (n = 3 independent fermentation runs), and results are reported as mean ± standard deviation to ensure reproducibility and statistical reliability.

Figure 3: Samples from the study

Prior to experimentation, both biomasses underwent standardized preconditioning, including drying, milling, and sieving, to obtain a homogeneous particle-size fraction (<1 mm). The prepared material was stored in a dedicated container to prevent moisture uptake prior to use. This preconditioning step ensured reproducibility and reduced variability associated with feedstock heterogeneity, in accordance with established biorefinery principles in which lignocellulosic biomass is fractionated into multiple value-added products, including biofuels and chemical intermediates (Al-Sahhaf et al., 2011). The overall experimental workflow followed a structured biomass-to-fuel conversion pathway as previously described in the literature (MME, 1982) and is schematically summarized in Figure 4, adapted from Al-Sahhaf et al. (2011), where biomass is converted into ethanol through sequential stages of pretreatment, hydrolysis, fermentation, and distillation, using water and yeast as key process inputs.

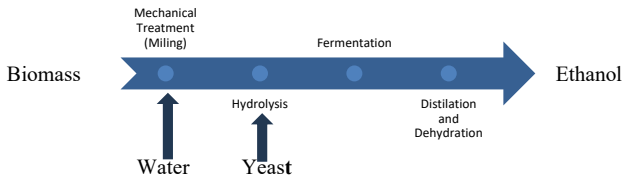


Figure 4: Obtaining Ethanol
Source: Simplified flowchart of the ethanol production process from lignocellulosic biomass, highlighting the sequential stages of pretreatment, hydrolysis, fermentation, and distillation (adapted from Al-Sahhaf et al., 2011).

Pretreatment was performed using dilute sulfuric acid hydrolysis to solubilize hemicellulosic fractions and improve cellulose accessibility. For each biomass, 50 g (dry basis) of material was mixed with 500 mL of 1.5% (v/v) H_2SO_4 solution at a solid-to-liquid ratio of 1:10 (w/v), then thermally treated in an autoclave at 121°C for 45–60 minutes. After cooling, the hydrolysate was neutralized to pH 5.0 ± 0.2 with 6 M NaOH, added gradually under constant stirring to control the exothermic nature of the neutralization reaction and avoid sugar degradation. This pH adjustment ensured optimal conditions for subsequent microbial activity.

Following pretreatment, vacuum filtration was employed to separate the liquid hydrolysate (sugar-rich fraction) from the solid cellulose-rich residue. The system consisted of a vacuum pump connected to a Kitasato flask and a porcelain funnel fitted with quantitative filter paper, ensuring efficient solid–liquid separation and reproducible recovery of fermentable sugars. The liquid fraction was directly used for fermentation, while the solid fraction was retained for enzymatic hydrolysis.

The pretreated solid fraction was subjected to enzymatic hydrolysis in 0.05 M acetate buffer (pH 4.8), using a commercial cellulolytic enzyme cocktail (15 FPU/g biomass). Hydrolysis was conducted in Erlenmeyer flasks at 50°C and 150 rpm for 72 hours, with samples collected periodically for reducing sugar analysis. Total reducing sugars (TRS) were quantified using the 3,5-dinitrosalicylic acid (DNS) method, as described by Miller (1959), with glucose used as a calibration standard.

Fermentation was carried out using Saccharomyces cerevisiae as the fermentative microorganism. The inoculum was prepared by activating yeast cells in sterile distilled water and pre-culturing in YPD medium 24 hours at 30°C until the exponential growth phase. The fermentation medium consisted of enzymatic hydrolysate supplemented with 0.05% $(NH_4)_2HPO_4$ as a nitrogen source. Fermentation was conducted in 100 mL working volume flasks, inoculated with 10% (v/v) active culture, and incubated at 30°C under static conditions for 72 hours. Ethanol production was monitored indirectly by CO_2 mass loss and confirmed through analytical quantification.

After fermentation, the broth was centrifuged at 5000 rpm for 10 minutes to remove microbial biomass, and the supernatant was distilled at 78–82°C to recover ethanol. To enhance ethanol purity, three successive distillation cycles were performed under identical operating conditions. The resulting ethanol was subsequently characterized by alcohol content, density, and combustion behavior.

Physicochemical characterization of both biomasses included immediate analysis (moisture content, volatile matter, ash, and fixed carbon) performed according to ASTM standards, as well as elemental analysis to determine carbon, hydrogen, nitrogen, sulfur, and oxygen contents. The higher heating value was estimated using validated empirical correlations. A qualitative Fuel Power Test was also conducted for demonstration purposes, acknowledging its observational nature and methodological limitations.

Although fermentation inhibitors were not quantified in this study, their potential presence due to acid pretreatment is acknowledged as a limitation. Statistical analysis was performed using Student's t-test for independent samples to evaluate differences in fermentation yields between sugarcane bagasse and Coconut shells, adopting a significance level of $\alpha = 0.05$. All experiments were conducted in triplicate, and results are expressed as mean ± standard deviation. Finally, we conducted a SWOT analysis of biomass's potential for ethanol production, with a view to its use as an additive in refining processes.

3. Results and Discussions

To characterize lignocellulosic biomass for bioadditive production, samples underwent various processes: characterization to evaluate properties, production to prepare the additive, and subsequent processes to add the additive to naphtha and evaluate its performance. For characterization processes, samples were subjected to the following analyses:

- Elemental analysis;
- Immediate analysis;
- Upper and lower calorific value.

For the production processes, microbial fermentation was conducted in the laboratory, followed by distillation. The results of the immediate analysis (Table 3) revealed significant differences in biomass. Bagasse had a moisture content 3.8 times higher than that of Coconut shell, a critical factor that directly impacts the process's energy balance, since the energy expended on drying can compromise overall efficiency.

Table 3: Results of immediate analysis

Parameter	Sugarcane bagasse	Coconut Shell	Relative Variation
Humidity (%)	36,55	9,6	+280%
Volatile (%)	73,54	77,53	+5,4%
Ashes (%)	5,0	7,02	+40,4%
Fixed carbon (%)	21,46	12,47	-41,9%

The calorific value analysis indicated that coconut shell presented a higher heating value (HHV = 16.44 MJ/kg), approximately 30.5% greater than that of sugarcane bagasse, indicating superior energy density. Fermentation performance showed differences between the two biomasses. Coconut shell achieved a mean ethanol yield of 90.42 ± 1.80%, while sugarcane bagasse reached 83.20 ± 2.10% (Table 4).

Table 4: Results of fermentation yield (n=3)

Biomass	Run 1 (%)	Run 2 (%)	Run 3 (%)	Mean (%)	Standard Deviation
Sugarcane bagasse	81.0	84.5	84.1	83.20	2.10
Coconut shell	88.9	91.2	91.6	90.42	1.80

The difference between fermentation yields was statistically evaluated using Student's t-test for independent samples ($\alpha = 0.05$). A statistically significant difference was observed between the two biomasses ($t = 4.87$; $p = 0.012$), indicating higher fermentation efficiency for coconut shell. The superior performance of coconut shell may be associated with differences in its physicochemical composition, lower moisture content, and greater structural stability during pretreatment and hydrolysis. The ethanol ob-

tained from both substrates exhibited high purity. Sugarcane bagasse-derived ethanol showed 93.10% (v/v), while coconut shell ethanol reached 93.99% (v/v). Density values were 0.809 g/mL and 0.815 g/mL, respectively.

Qualitative combustion tests indicated complete combustion for both ethanol samples, with no detectable solid residue after burning. Burning times were 4 minutes for bagasse-derived ethanol and 2 minutes for coconut shell ethanol, reflecting minor differences in fuel characteristics. To test the density and alcohol content, we placed the thermometer and hydrometer in the sample, waited a few minutes for the thermometer and hydrometer to stabilize, observed that the alcohol was at 26°C and 23°C for the two samples, respectively, consulted the conversion Table 5, and obtained the following results:

Table 5: Bagasse ethanol density test

Type of biofuel	Temperature (ºC)	Density (g/ml)	Alcohol content (v/v)
Ethanol from sugarcane bagasse	26ºC	0,809	93,10
Ethanol from coconut shells	23ºC	0,815	93,99

Elemental analysis (Table 6) showed a higher C/O ratio for coconut shell (1.35) compared to bagasse (1.10). Sulfur content remained low in both materials (300 ppm and 1200 ppm, respectively), while nitrogen content was higher in coconut shell (2.98%) than in bagasse (0.90%).

Table 6: Critical elementary challenges

Parameter	Bagasse	Coconut Shell	Technical Implication
Ratio C/O	1,10	1,35	Greater energy potential from the husk
S content (ppm)	300	1200	Both below the limit for clean fuels (<5000 ppm)
N content (%)	0,90	2,98	Shell may require NOx emissions control

The following chart (Figures 5 and 6) provides a better visualization of the information in the previous Table.

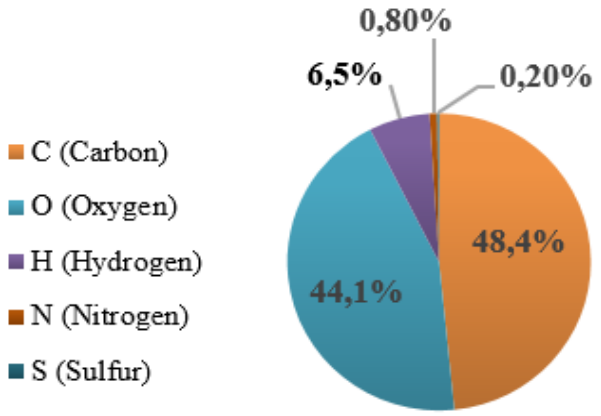


Figure 5: Elemental composition of biomass (Sugarcane Bagasse)

Figures 5 and 6 present a comparison of the typical elemental composition of biomass, based on the C/O ratio and experimentally determined N and S contents, supplemented with literature values. A higher relative fraction of carbon is observed in Coconut shells, in line with their higher energy potential. Biomass with higher C/O and high volatile content is more suitable for fast pyrolysis and gasification, while materials with higher ash and N content require environmental mitigation strategies.

The extremely low sulfur content (<0.12%) is a decisive environmental advantage, positioning these biofuels as “low-sulfur fuel” alternatives to petroleum derivatives. To statistically validate the difference observed in yields, Student's t-test for independent samples was applied. The results revealed a significant difference ($p < 0.05$) between the average yields.

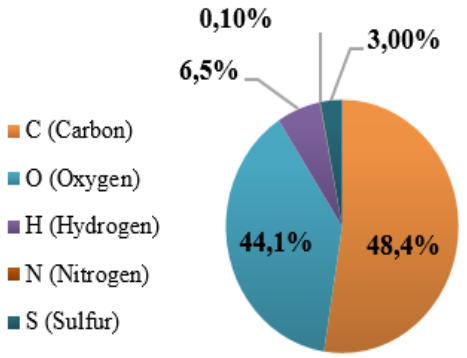


Figure 6: Elemental composition of biomass (Coconut Shell)

The fermentation performance of the two lignocellulosic feedstocks showed measurable differences under identical processing conditions. Sugarcane bagasse achieved a mean ethanol yield of 83.20 ± 2.10%, while coconut shell reached 90.42 ± 1.80% (Table 8).

Table 8: Statistical analysis of fermentation yields

Analysis	Sugarcane bagasse	Coconut Shell
Average (%)	83,20	90,42
Standard deviation	2,1	1,8
Calculated t-value	4,87	
p value	0,012	
Conclusion	Statistically significant difference (p < 0,05)	

The variability within each dataset remained low (CV < 3%), with coefficients of variation of 2.5% for sugarcane bagasse and 2.0% for coconut shells, indicating good experimental repeatability across the triplicate runs. Students’ t-test for independent samples confirmed that the difference between the means is statistically significant ($t = 4.87$; $p = 0.012$; $\alpha = 0.05$), indicating higher fermentation performance for coconut shell under the conditions studied. This analysis is shown in Figure 7, which compares fermentation yields.

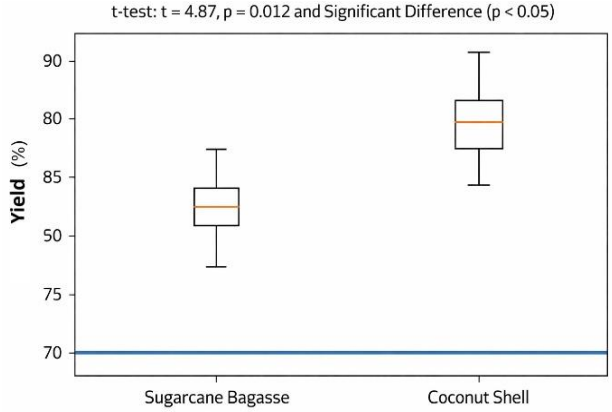


Figure 7: Comparative analysis of fermentation yields

Figure 7 corroborates the statistical results in Table 8, showing a significantly higher fermentation yield for coconut shell (90.42%) than for sugarcane bagasse (83.20%). Student’s t-test confirmed that this difference was statistically significant ($t = 4.87$; $p = 0.012$; $\alpha = 0.05$). The low coefficients of variation (<3%) indicate good experimental repeatability and support the robustness of the observed difference. Under the investigated pretreatment, hydrolysis, and fermentation conditions, coconut shell exhibited superior fermentation performance, possibly due to differences in biomass composition and reduced formation of inhibitory compounds.

To objectively quantify biomass's potential as a raw material for additives, a SWOT analysis was conducted to assess its potential for ethanol production. This study demonstrated the principle of converting lignocellulosic waste into ethanol but showed that the pretreatment/hydrolysis protocol used is the critical bottleneck for technical and economic viability (Table 9).

Table 9: SWOT Analysis of Biomass Potential

Factor	Sugarcane bagasse	Coconut Shell
Strengths (Technical)	High availability, low cost, low ash content	High energy density (PCS), greater release of sugars observed
Weaknesses (Technical)	High humidity, low ethanol concentration in the current process	Collection logistics, higher ash and nitrogen content
Opportunities	Integration with first-generation biorefineries (existing plants)	Urban/seasonal waste recovery
Threats/Challenges	Need for drastic optimization of pretreatment	Need to remove inhibitors/nitrogen compounds

For this ethanol to be considered a viable additive for gasoline, the following are required, at a minimum: 1) an increase in ethanol concentration in the mash to >40 g/L (distillation feasibility); 2) Confirmation of the purity and physicochemical properties of ethanol according to standardized specifications; 3) blending tests (e.g., E10) and evaluation of performance in engines. Coconut shells showed slightly better indicators for sugar release, while bagasse has logistical advantages. Both routes require significant research into process optimization before any large-scale assessment of their potential.

The physicochemical characterization of the evaluated lignocellulosic biomasses confirms their suitability for bioconversion processes and highlights important structural and compositional differences that directly influence process performance.

Sugarcane bagasse exhibited a markedly higher moisture content (36.55%) compared to coconut shell (9.6%), reflecting intrinsic differences in porosity, capillary structure, and water retention capacity. Such behavior is consistent with the findings of Fengel and Wegener (1989), who demonstrated that the architecture of the lignocellulosic matrix strongly governs moisture adsorption and transport in biomass. From a process engineering perspective, this elevated moisture content in bagasse imposes an additional energy burden during drying, potentially reducing the overall energy efficiency of downstream conversion processes.

In contrast, coconut shell exhibited superior energy performance, with a higher heating value (HHV = 16.44 MJ/kg), approximately 30.5% higher than that of sugarcane bagasse. This difference is primarily attributed to its higher lignin fraction and more compact structural arrangement, which enhance energy density. As reported by Lin et al. (2010), lignin-rich biomass typically exhibits higher calorific values due to its more reduced chemical state and aromatic structure.

The fermentation performance further corroborates these differences. Coconut shell achieved a significantly higher ethanol yield (90.42 ± 1.80%) than sugarcane bagasse (83.20 ± 2.10%), as statistically validated ($t = 4.87$; $p = 0.012$). The lower variability observed across replicates (CV < 3%) indicates good experimental reproducibility and reinforces the robustness of the comparative assessment.

This superior performance of coconut shell may be linked to its lower moisture content and greater structural resistance to pretreatment, which likely improves the accessibility of fermentable fractions. Girio et al. (2010) emphasize that lignocellulosic heterogeneity, particularly in hemicellulosic composition, plays a critical role in hydrolysis efficiency and the release of fermentable sugars, which directly affects ethanol yield.

Elemental analysis further supports the energetic advantage of the coconut shell. The higher C/O ratio (1.35 vs. 1.10) indicates greater carbon enrichment, which is typically associated with higher energy potential. However, the elevated nitrogen content in coconut shell suggests a potential drawback: NOx formation during combustion or thermochemical conversion, which may necessitate adequate emission control strategies.

The low sulfur content observed in both biomasses represents a strong environmental advantage, positioning both feedstocks as suitable candidates for low-sulfur biofuel production, with reduced environmental impact compared to conventional fossil-derived fuels.

From a process integration perspective, both biomasses demonstrate complementary characteristics. Sugarcane bagasse benefits from established industrial availability and easier integration into existing biorefinery infrastructure, while coconut shell offers superior energy density and higher fermentation efficiency under identical processing conditions.

The statistical significance of the fermentation results confirms that biomass type has a measurable effect on conversion efficiency under the studied conditions. However, despite the higher yields observed for coconut shell, both substrates still present ethanol concentrations below the threshold required for economically viable industrial distillation (>40 g/L), indicating that process intensification remains necessary.

In this context, the results suggest that pretreatment and hydrolysis efficiency are the primary limiting steps in the overall bioconversion pathway. Improvements in enzymatic accessibility, inhibition control, and process configuration (e.g., shift from SHF to SSF systems) are expected to significantly enhance sugar release and fermentation performance.

The SWOT analysis confirms that both feedstocks possess technical potential for integration into biorefinery systems, although with distinct limitations. Sugarcane bagasse offers logistical and infrastructural advantages, while coconut shell provides superior energy performance but may require additional considerations regarding supply chain logistics and nitrogen-associated emissions. These results reinforce the viability of integrating lignocellulosic biomass into industrial energy transition systems, in consonance with studies by Lora and Venturini (2012), Aguiar et al. (2020), as well as recent works by Morais et al. (2022b; 2023).

Overall, the results indicate that lignocellulosic biomass valorization for ethanol production is technically feasible but still constrained by pretreatment efficiency and downstream sugar concentration limitations. The statistical significance of the fermentation results ($p = 0.012$) confirms that biomass type has a measurable effect on conversion efficiency under the studied conditions, with coconut shell showing superior performance. However, despite the higher yields observed for coconut shell, both substrates still present ethanol concentrations below the threshold required for economically viable industrial distillation (>40 g/L), indicating that process intensification remains necessary. Therefore, future work should prioritize process intensification strategies to bridge the gap between laboratory-scale feasibility and industrial viability.

4. Conclusion

The objective of this study was to evaluate the *theoretical* potential of sugarcane bagasse and coconut shells as feedstocks for producing ethanol for use as a refinery additive. While the proof-of-concept was successful on a laboratory scale, the results demonstrate that under the current, non-optimized conditions, this application remains a future perspective rather than a near-term reality. The following critical limitations were identified: (i) extremely low ethanol titters (~6 g/L) far below the economic distillation threshold (>40 g/L); (ii) the need for energy-intensive dehydration to break the water-ethanol azeotrope; and (iii) the presence of inhibitory compounds that reduce fermentation efficiency.

The physicochemical characterization of the biomass provided the following valuable insights:

i. Sugarcane bagasse: Notable for its high availability and low logistics costs, but its high moisture content (36.55%) poses a significant technical and economic challenge for pre-processing.
ii. Coconut Shell: It has higher energy density and lower moisture content, positioning itself as a waste product with high potential for recovery. However, the logistics of collection and its higher inorganic content (ash and nitrogen) are points to consider.
iii. Common Environmental Advantage: Both types of biomasses have very low sulfur content, which is a clear environmental advantage as a raw material for “cleaner” fuels.
iv. However, ethanol obtained via simple distillation had a purity of around 93% v/v (hydrated alcohol). To be used as an additive in gasoline (e.g., in E10 and E25 blends), anhydrous ethanol (content >99.5% v/v) is required, necessitating additional dehydration steps. Furthermore, the economic viability of the process depends on achieving ethanol concentrations in the must above 40 g/L, making distillation energetically viable. The current study does not meet any of these technical requirements for immediate application.

For the potential of these biomasses to be effectively evaluated to produce a refining additive, future research should focus on:

i. Systematic Optimization of Pretreatment: Test and model different conditions to maximize sugar yield and minimize inhibitors.
ii. Increased Solids Concentration: Perform hydrolysis and fermentation with a higher biomass load to increase the final ethanol concentration.

iii. Detailed Analysis of Hydrolysates: Employ techniques such as HPLC to specifically quantify the released sugars (glucose, xylose) and the presence of inhibitors (furfural, acetic acid, HMF).
iv. Validation as an Additive: Produce anhydrous ethanol from the optimized process and perform blending tests with gasoline, evaluating critical properties such as octane rating, vapor pressure, and stability, in addition to engine performance tests.

This work serves as valuable preliminary research, confirming the principle of conversion and clearly identifying the critical points hindering the process's viability. Both sugarcane bagasse and Coconut shells have interesting attributes in the context of biorefineries and the circular economy. However, the results do not allow us to affirm that, under current conditions, they are viable raw materials for large-scale additive ethanol production. The technological route explored requires significant advances in research and development, particularly in the pretreatment stage, to translate the theoretical potential of these abundant residues into a concrete, sustainable alternative for the fuel sector. Study thus fulfills its role by mapping the challenges and guiding the efforts needed to overcome them.

The results suggest that future research should focus on implementing Simultaneous Saccharification and Fermentation (SSF) configurations, developing advanced distillation techniques to achieve ethanol purity exceeding 99% (v/v), and evaluating the costs of integrating these technologies into industrial refining systems.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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