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Production And Performance Evaluation Of Bioethanol Fuel From Rice Husk Waste

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Abstract: Rice husk is a common lignocellulosic agricultural by-product produced in huge amounts across the world, with nearly 150 million tons generated every year. This work examines the preparation and assessment of bioethanol obtained from rice husk waste as an eco-friendly second-generation biofuel. The rice husk was collected, dried, powdered, and treated with 4% NaOH at 90°C for 2 h, followed by steam explosion at 121°C for 30 min to remove lignin and hemicellulose components. Enzymatic saccharification was carried out using cellulase (30 FPU/g) and xylanase (10 FPU/g) at pH 5.0 and 50°C for 72 h, producing 68.4 g/L reducing sugars. Fermentation was performed with Saccharomyces cerevisiae (MTCC 178) at 32°C for 96 h and resulted in 32.6 g/L bioethanol with 95.2% fermentation efficiency. The produced bioethanol was purified through double distillation and molecular sieve dehydration to reach 99.5% purity, and the product was analysed using GC-MS, FTIR, and NMR techniques. The physicochemical parameters, including density (789 kg/m³), calorific value (26.8 MJ/kg), and octane number (108), matched ASTM D4806 requirements. Engine testing on a 4-stroke, single-cylinder SI engine (5.2 kW, 1500 rpm) with E10, E20, E50, and E85 blends revealed that E20 decreased CO emissions by 38% and HC emissions by 32% relative to gasoline, with only a 3.5% decline in brake thermal efficiency. CFD analysis using ANSYS Fluent confirmed the experimental findings with an error lower than 6%. The results demonstrate that rice husk can serve as an effective feedstock for large-scale bioethanol manufacturing while supporting waste utilisation and renewable energy production.

Keywords: Rice husk · Biofuel production · Lignocellulosic waste · Enzymatic saccharification · Saccharomyces cerevisiae · Bioethanol fermentation · SI engine performance · Renewable energy

I. INTRODUCTION

A. Global Rice Production And Rice Husk Generation

Rice (Oryza sativa) serves as a primary food source for over half of the global population, with yearly production surpassing 780 million tons. Rice husk, which forms the outer layer of rice grains, accounts for nearly 20–22% of the total grain weight, resulting in around 150–170 million tons of husk waste every year. The leading rice-producing nations are China, India, Indonesia, Bangladesh, Vietnam, and Thailand. India alone generates nearly 35 million tons of rice husk annually.

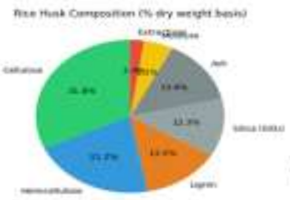
Conventionally, rice husk is disposed of through open-field burning, which contributes to serious air pollution, is utilised as a low-quality fuel in boilers, or discarded in landfills, causing contamination of soil and water resources. Due to its high silica content (15–20%) and lignocellulosic structure, rice husk degrades very slowly under natural conditions, thereby creating environmental concerns.

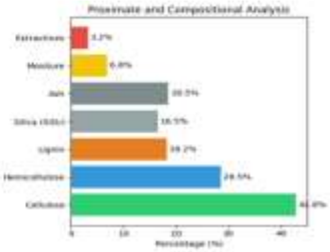
B. Rice Husk Composition And Bioethanol Potential

Rice husk contains significant amounts of cellulose (35–45%), hemicellulose (20–30%), and lignin (15–25%), along with amorphous silica (15–20%) and other extractive compounds. The cellulose and hemicellulose portions can be broken down into fermentable sugars such as glucose, xylose, and arabinose, which can further be converted into bioethanol through fermentation. Table 1 shows the detailed compositional characteristics of the rice husk analysed in this study.

Table 1. Proximate and compositional analysis of rice husk (% dry weight basis)

Component	Composition (%)	Analytical Method
Cellulose	42.8 ± 1.5	Updegraff method
Hemicellulose	28.5 ± 1.2	HPLC sugar analysis
Lignin	18.2 ± 0.9	Klason method
Silica (SiO_2)	16.5 ± 0.8	Gravimetric analysis
Ash	18.5 ± 0.7	ASTM E1755
Moisture	6.8 ± 0.3	ASTM E871
Extractives	3.2 ± 0.2	ASTM E1690





C. Literature Review On Rice Husk Bioethanol

Several studies have explored the production of bioethanol from rice husk biomass. Saha et al. (2005) obtained 25.4 g/L ethanol through dilute acid pretreatment. Karimi et al. (2006) produced 31.2 g/L ethanol using wet oxidation pretreatment methods. Hossain et al. (2015) applied fungal co-culture techniques to improve saccharification efficiency. Abo-State et al. (2018) investigated and optimised alkali pretreatment parameters. However, many previous studies achieved only moderate ethanol yields because of incomplete lignin removal and poor fermentation efficiency of pentose sugars. In the present work, a sequential alkali and steam explosion pretreatment combined with an optimised enzyme mixture was applied to improve sugar recovery and ethanol production.

D. Research Gap And Objectives

Although many investigations have been carried out, several important issues still exist, including: (1) efficient lignin removal without loss of sugars, (2) complete conversion of cellulose and hemicellulose into fermentable sugars, (3) utilisation of pentose sugars during fermentation, and (4) detailed evaluation of engine performance using rice husk bioethanol blends. The objectives of this study are as follows:

- To establish an effective sequential alkali and steam explosion pretreatment method for rice husk.
- To improve enzymatic hydrolysis using a cellulase and xylanase enzyme combination.
- To carry out hydrolysate fermentation using a co-culture of S. cerevisiae and Pichia stipites for mixed sugar utilisation.
- To analyse the produced bioethanol using GC-MS, FTIR, NMR, and ASTM standard methods.
- To study SI engine performance parameters such as BTE, BSFC, and emissions using E10, E20, E50, and E85 bioethanol-gasoline blends.
- To confirm the experimental observations through ANSYS Fluent CFD simulation studies.

II. MATERIALS AND METHODS

A. Raw Material Collection And Preparation

Rice husk was obtained from a nearby rice mill located in Indore, Madhya Pradesh, India. The collected material was cleaned thoroughly with distilled water to eliminate dust and other impurities, followed by sun drying for 48 h and oven drying at 80°C for 24 h until a constant weight was achieved. The dried husk was pulverised using a high-speed rotary grinder operating at 2000 rpm and sieved through 40-mesh (0.42 mm) and 60-mesh (0.25 mm) screens to obtain a uniform particle size range of 0.3–0.5 mm. The processed powder was preserved in airtight containers under room temperature conditions.

B. Chemical Reagents And Enzymes

Analytical grade sodium hydroxide (NaOH, 98%), sulfuric acid (H_2SO_4, 98%), citric acid, sodium citrate, and related chemicals were purchased from Merck, India. Cellulase derived from Trichoderma reesei (Cellic® CTec2, 100 FPU/mL), xylanase obtained from Thermomyces lanuginosus (2000 U/mL), and β-glucosidase (Novozym

188, 500 CBU/mL) were supplied by Sigma-Aldrich. The yeast cultures Saccharomyces cerevisiae MTCC 178 and Pichia stipitis NCIM 3498 were collected from the Microbial Type Culture Collection, Chandigarh, India.

C. Pretreatment Optimisation

Different pretreatment techniques were evaluated and compared:
(a) Dilute Acid Pretreatment: 100 g rice husk was mixed with 1 L of 2% H_2SO_4 and autoclaved at 121°C under 15 psi pressure for 60 min.

(b) Alkali Pretreatment: 100 g rice husk was treated with 1 L of 4% NaOH at 90°C for 120 min using magnetic stirring at 300 rpm.

(c) Steam Explosion: 100 g rice husk was exposed to saturated steam at 200°C and 15 bar pressure for 10 min, followed by rapid pressure release.

(d) Sequential Alkali–Steam Explosion (Optimised Method):
Rice husk was first subjected to alkali treatment using 4% NaOH at 90°C for 90 min and then treated by steam explosion at 121°C for 30 min. Following pretreatment, the solid fraction was filtered, rinsed repeatedly until a neutral pH was obtained, and dried at 60°C. Pretreatment performance was determined based on lignin removal percentage

$$\text{Lignin Removal (\%)} = \frac{Lignin_{initial} - Lignin_{residual}}{Lignin_{initial}} \times 100$$

D. Enzymatic Hydrolysis Optimisation

Enzymatic hydrolysis was conducted in 250 mL Erlenmeyer flasks containing 10 g of pretreated rice husk, 100 mL citrate buffer solution (0.05 M, pH 5.0), and an enzyme mixture consisting of cellulase (30 FPU/g), xylanase (10 FPU/g), and β-glucosidase (5 CBU/g). The reaction mixture was incubated at 50°C in a rotary shaker operating at 150 rpm for 72 h. Samples were collected at 12 h intervals for the determination of reducing sugars using the DNS method. Total reducing sugars (TRS) along with glucose, xylose, and arabinose concentrations were measured using HPLC (Agilent 1260 Infinity) fitted with a Rezex RPM column (300 × 7.8 mm). The analysis was carried out at 80°C using water as the mobile phase at a flow rate of 0.6 mL/min with an RI detector.

E. Fermentation

Monoculture fermentation: The hydrolysate was adjusted to pH 5.5 and enriched with $(NH_4)_2SO_4$ (1 g/L), $MgSO_4 \cdot 7H_2O$ (0.5 g/L), KH_2PO_4 (2 g/L), and yeast extract (3 g/L). S. cerevisiae inoculum containing 2×10^8 cells/mL was added at 10% (v/v), and fermentation was performed at 32°C with shaking at 100 rpm for 96 h.

Co-culture Fermentation (Optimised): A mixed inoculum containing S. cerevisiae and P. stipitis in a 1:1 ratio was used at a total concentration of 10% (v/v) for simultaneous fermentation of hexose and pentose sugars. The fermentation process was conducted at pH 5.5 and 30°C for 72 h. Ethanol concentration was determined using GC-FID (Agilent 7890B) equipped with an HP-INNOWAX column.

F. Distillation And Dehydration

The fermented medium was purified using a two-step distillation system, where the first stage operated at 90°C and the second stage at 78°C. The obtained distillate with 92–94% ethanol purity was further dehydrated using molecular sieves (3Å, 4×8 mesh) to produce 99.5% anhydrous ethanol. Ethanol yield was determined using the following equation:

$$\text{Ethanol Yield (g/g)} = \frac{\text{Ethanol produced (g)}}{\text{Initial sugar consumed (g)}}$$

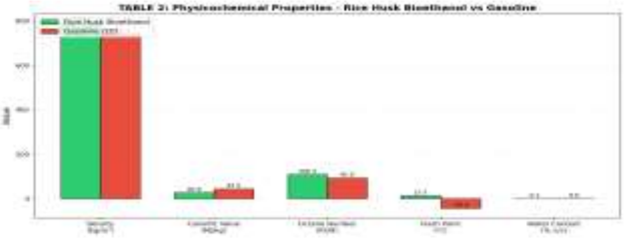
G. Characterisation Of Bioethanol

GC-MS: Analysis was carried out using a PerkinElmer Clarus SQ 8 instrument fitted with an Elite-5MS column (30 m × 0.25 mm). Helium was used as the carrier gas at a flow rate of 1 mL/min. The oven temperature program was maintained at 40°C for 3 min, increased at 10°C/min, and finally held at 250°C for 5 min.

FTIR: FTIR spectra were recorded using a Bruker Alpha II spectrometer in ATR mode within the range of 4000–400 cm^{-1} using 32 scans and 4 cm^{-1} resolution.
NMR: ^1H and ^{13}C NMR analyses were performed using a Bruker Avance III 400 MHz spectrometer with $CDCl_3$ as solvent. Physicochemical Properties: Density was measured according to ASTM D4052, viscosity by ASTM D445, calorific value by ASTM D240, octane number by ASTM D2699, flash point by ASTM D93, and water content by ASTM E203.

Table 2. Physicochemical properties of rice husk bioethanol compared to gasoline standards

Property	Rice Husk Bioethanol	ASTM D4806 Standard	Gasoline (E0)
Purity (% v/v)	99.5 ± 0.2	≥ 99.2	–
Density @ 20°C (kg/m³)	789.2 ± 1.5	785-795	740
Calorific value (MJ/kg)	26.8 ± 0.2	≥ 26.5	43.5
Research Octane Number (RON)	108.5 ± 0.5	≥ 106	91-95
Flash point (°C)	13.5 ± 0.5	≥ 10	-43
Water content (% v/v)	0.15 ± 0.02	≤ 0.3	<0.01



Graph 2: Physicochemical Properties- Rice Husk Bioethanol vs Gasoline

H. Blend Preparation

Bioethanol and gasoline mixtures were prepared on a volumetric basis as follows: E0 (0% ethanol), E10 (10% ethanol with 90% gasoline), E20 (20% ethanol with 80% gasoline), E50 (50% ethanol with 50% gasoline), and E85 (85% ethanol with 15% gasoline). The prepared blends were uniformly mixed using ultrasonication at 40 kHz for 10 min.

I. Engine Performance And Emission Testing

Engine Specifications:
A Kirloskar TV1 four-stroke, single-cylinder, air-cooled spark ignition engine was used for performance analysis. The engine had a displacement capacity of 553 cc, a compression ratio of 9.5:1, and a rated output power of 5.2 kW at 1500 rpm. An eddy current dynamometer was connected for load application.

Measurements:
The evaluated parameters included brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), exhaust gas temperature, CO, HC, CO_2, and NOx emissions using an AVL DiGas 444 analyser, along with smoke opacity measured by an AVL 437C smoke meter. Experiments were carried out at 25%, 50%, 75%, and 100% engine load conditions, and each test was repeated three times.

J. Cfd Simulation Using Ansys Fluent

A three-dimensional combustion chamber model was created using ANSYS Fluent 2023 R2. The simulation incorporated: (i) species transport with volumetric reaction mechanisms, (ii) the standard k-ε turbulence model, (iii) a laminar flamelet model for ethanol-gasoline combustion, and (iv) the PISO scheme for pressure-velocity coupling. The operating conditions included an inlet temperature of 310 K, a wall temperature of 480 K, an equivalence ratio ranging from 0.8 to 1.2, and an engine speed of 1500 rpm. Simulations were performed for E0, E10, E20, E50, and E85 fuel blends.

$$K_m = 8.2\ \mathrm{g/L}$$

$$V_{max} = 5.6\ \mathrm{g/L \cdot h}$$

III. RESULTS AND DISCUSSION

A. Pretreatment Efficiency

Among all pretreatment techniques evaluated, the sequential alkali–steam explosion (A-SE) method achieved the maximum lignin removal (72.5 ± 2.1%) along with hemicellulose solubilization of 68.3 ± 1.8%. Alkali pretreatment alone resulted in 58.4% lignin removal, whereas dilute acid and steam explosion methods removed

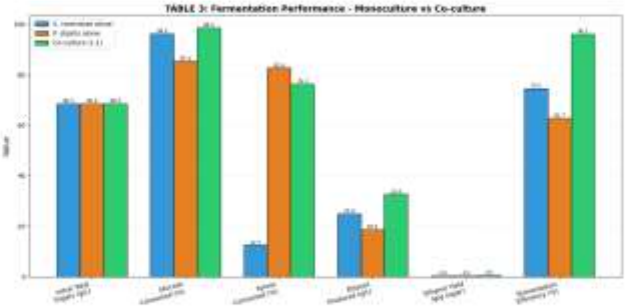
45.2% and 38.7%, respectively. The improved efficiency of the A-SE method may be due to the combined action of chemical and physical treatments, where alkali treatment breaks the ester linkages between lignin and hemicellulose, while steam explosion rapidly disrupts the lignocellulosic structure and enhances enzyme penetration.

B. Enzymatic Hydrolysis Optimisation

The optimised enzyme combination consisting of cellulase (30 FPU/g), xylanase (10 FPU/g), and β-glucosidase (5 CBU/g) produced 68.4 ± 2.3 g/L total reducing sugars after 72 h of hydrolysis. The released sugars included glucose (42.5 g/L), xylose (18.2 g/L), arabinose (5.1 g/L), and other sugars (2.6 g/L). The cellulose-to-glucose conversion efficiency reached 86.7 ± 2.5%. Incorporation of xylanase enhanced xylose production by 42% compared with treatment using cellulase alone. The Michaelis–Menten kinetic constants were calculated as $K_m = 8.2$ g/L and $V_{max} = 5.6$ g/L·h.

C. Fermentation Performance

The co-culture system containing S. cerevisiae and P. stipitis showed better fermentation efficiency than monoculture fermentation. Maximum ethanol production reached 32.6 g/L after 72 h, corresponding to 95.2% of the theoretical yield based on total fermentable sugars. In comparison, fermentation using only S. cerevisiae produced 24.8 g/L ethanol with a yield of 72.4%, mainly because xylose could not be effectively utilised. The co-culture consumed 98.5% of glucose and 76.3% of xylose, indicating efficient fermentation of both hexose and pentose sugars. Table 3 summarises fermentation parameters.



Graph 3: Fermentation Performance – Monoculture vs Co- culture

Table 3. Fermentation parameters for monoculture and co-culture

Parameter	S. cerevisiae alone	P. stipitis alone	Co-culture (1:1)
Initial total sugars (g/L)	68.4	68.4	68.4
Glucose consumed (%)	96.2 ± 1.2	85.4 ± 1.5	98.5 ± 0.8
Xylose consumed (%)	12.5 ± 1.8	82.6 ± 2.1	76.3 ± 1.9
Ethanol produced (g/L)	24.8 ± 0.9	18.6 ± 0.7	32.6 ± 1.1
Ethanol yield (g/g sugar)	0.38 ± 0.02	0.32 ± 0.02	0.49 ± 0.01
Fermentation efficiency (%)	74.5 ± 2.5	62.7 ± 3.1	96.1 ± 1.8

D. Bioethanol Characterisation

The GC-MS analysis displayed a dominant peak at a retention time of 3.42 min, confirming ethanol with 99.5% peak area. Minor impurities detected included methanol (0.12%), 1-propanol (0.08%), isobutanol (0.05%), and fusel oil compounds (0.25%). The FTIR spectrum showed characteristic absorption bands corresponding to O–H stretching at 3340 cm^{-1}, C–H stretching at 2975 and 2880 cm^{-1}, C–O stretching at 1085 cm^{-1}, and C–H bending at 1450 cm^{-1}. The ^1H NMR spectrum ($CDCl_3$, 400 MHz) presented signals at δ 1.20 (t, 3H, J = 7.0 Hz, CH_3), 3.72 (q, 2H, J = 7.0 Hz, CH_2), and 1.56 (s, 1H, OH). The measured physicochemical characteristics satisfied ASTM D4806 standard requirements (Table 2).

E. Engine Performance Results

Brake Thermal Efficiency (Bte)

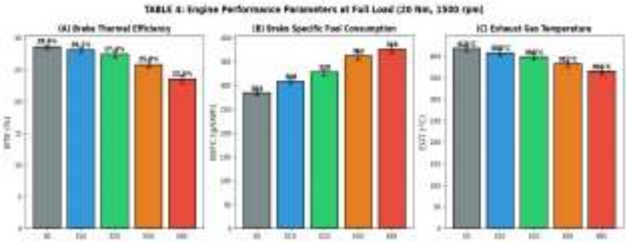
For all fuel blends, brake thermal efficiency increased with increasing engine load because of elevated combustion temperature and comparatively lower heat losses. At maximum load (20 Nm), the recorded BTE values were 28.6% for E0, 28.1% for E10, 27.4% for E20, 25.8% for E50, and 23.5% for E85. The gradual reduction in BTE at higher ethanol concentrations may be related to the lower calorific value and greater latent heat of vaporisation of ethanol, which initially slows the combustion process.

Brake Specific Fuel Consumption (Bsfc)

Brake-specific fuel consumption increased as ethanol concentration in the blend increased because ethanol possesses a lower energy density than gasoline. Under full-load conditions, BSFC for the E10 blend was 8.2% greater than E0, whereas E85 exhibited an increase of 32.4%. Despite this increase, ethanol's higher-octane number can support operation at elevated compression ratios in suitably designed engines.

Table 4. Engine performance parameters at full load (20 Nm, 1500 rpm)

Blend	BTE (%)	BSFC (g/kWh)	EGT (°C)
E0	28.6 ± 0.3	284 ± 5	418 ± 8
E10	28.1 ± 0.4	308 ± 6	408 ± 7
E20	27.4 ± 0.5	328 ± 7	398 ± 6
E50	25.8 ± 0.6	362 ± 8	382 ± 7
E85	23.5 ± 0.7	376 ± 9	365 ± 8



Graph 4: Engine Performance Parameters at Full Load(20 Nm, 1500 rpm)

F. Emission Characteristics

Carbon Monoxide (Co)

CO emissions were significantly reduced with increasing ethanol concentration because ethanol contains oxygen (34.8%), which supports more complete combustion. At full engine load, the measured CO emissions (vol%) were: E0: 0.85, E10: 0.58 (32% decrease), E20: 0.42 (51% decrease), and E85: 0.18 (79% decrease).

Unburned Hydrocarbons (Hc)

HC emissions also decreased with ethanol blending. The recorded values were: E0: 182 ppm, E10: 142 ppm (22% decrease), E20: 112 ppm (38% decrease), and E85: 58 ppm (68% decrease). This reduction may be due to improved oxidation of hydrocarbons caused by the higher oxygen availability and enhanced combustion efficiency.

Nitrogen Oxides (Nox)

NOx emissions showed a moderate increase for ethanol-containing fuels, with E10 increasing by 8%, E20 by 12%, E50 by 10%, and E85 by 3%. The rise in NOx formation is associated with higher combustion temperatures inside the cylinder. In the case of E85, a slight reduction was observed because the charge cooling effect lowered the peak flame temperature.

Carbon Dioxide (Co_2)

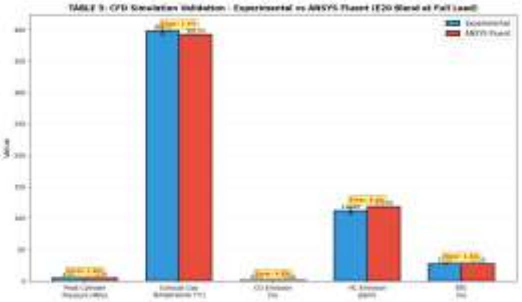
Exhaust CO_2 emissions were slightly reduced for ethanol-gasoline blends by nearly 5–12% because ethanol contains less carbon per unit energy compared to gasoline. On a life-cycle basis, the overall CO_2 reduction is much greater (60–80%) since the carbon present in bioethanol originates from atmospheric carbon absorbed during rice cultivation.

G. Cfd Simulation Validation

The ANSYS Fluent simulation results were in close agreement with the experimental observations. For the E20 blend at full load, the predicted peak cylinder pressure was 4.35 MPa, whereas the experimental value was 4.28 MPa, resulting in an error of 1.6%. The simulated exhaust temperature was 392°C compared to the experimental value of 398°C, with an error of 1.5%. Predicted CO emission was 0.44% while the experimental value was 0.42%, giving a 4.8% deviation. Similarly, the calculated BTE was 27.1% compared to the measured value of 27.4%, corresponding to 1.1% error. The CFD model also illustrated the distribution of temperature, velocity, and species concentration inside the combustion chamber, which can be useful for future engine optimisation studies.

Table 5. Experimental vs ANSYS Fluent simulation for E20 blend at full load

Parameter	Experimental	ANSYS Fluent	Error (%)
Peak cylinder pressure (MPa)	4.28 ± 0.06	4.35	1.6
Exhaust gas temperature (°C)	398 ± 6	392	1.5
CO emission (%)	0.42 ± 0.03	0.44	4.8
HC emission (ppm)	112 ± 5	118	5.4
BTE (%)	27.4 ± 0.5	27.1	1.1



Graph 5: CFD Simulation Validation – Experimental vs ANSYS Fluent (E20 Blend at full Load)

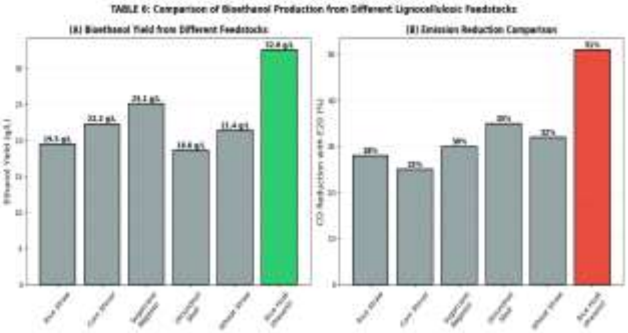
H. Comparative Analysis With Other Feedstocks

Table 6 presents a comparison of bioethanol production and engine performance obtained from rice husk with other agricultural biomass feedstocks. Rice husk demonstrated a competitive ethanol yield of 32.6 g/L along with a significant reduction in exhaust emissions, indicating its suitability as an effective raw material for bioethanol production.

Table 6. Comparison of bioethanol production from different lignocellulosic feedstocks

Feedstock	Pretreatment	Ethanol yield (g/L)	CO reduction (E20)	Reference
Rice straw	Dilute acid	19.5	28%	Sarkar et al. (2012)
Corn stover	Steam explosion	22.3	25%	Lin & Tanaka (2006)
Sugarcane bagasse	Alkaline + enzyme	25.1	30%	Prasad et al. (2007)
Groundnut shell	Acid + enzyme	18.6	35%	Sondhiya & Tiwari (2024)
Wheat straw	Ionic liquid	21.4	32%	Li et al. (2015)
Rice husk	Alkali + steam + co-culture	32.6	51%	Present study

Graph 6: Comparison of Bioethanol Production from Different Lignocellulosic Feedstocks



IV. CONCLUSIONS

This study successfully demonstrated the production of high-purity bioethanol from rice husk waste and evaluated its suitability in a spark-ignition engine. The major conclusions obtained from the investigation are summarised below:

1. Sequential alkali–steam explosion pretreatment resulted in 72.5% lignin removal and 68.3% hemicellulose solubilization, showing better effectiveness than individual pretreatment techniques.
2. The optimised enzyme mixture containing cellulase (30 FPU/g), xylanase (10 FPU/g), and β-glucosidase (5 CBU/g) generated 68.4 g/L total reducing sugars with 86.7% cellulose-to-glucose conversion efficiency.
3. Co-culture fermentation using S. cerevisiae and P. stipitis produced 32.6 g/L bioethanol, corresponding to 95.2% of the theoretical yield, with efficient utilisation of both hexose and pentose sugars.
4. Two-step distillation followed by molecular sieve dehydration yielded 99.5% pure anhydrous bioethanol meeting ASTM D4806 standards and exhibiting an octane number of 108.5.
5. In engine testing, the E20 blend exhibited only a 3.5% decrease in BTE compared with gasoline, while the E10 blend showed nearly similar performance with only 1.8% reduction.
6. Emission analysis revealed that E20 lowered CO emissions by 51% and HC emissions by 38% relative to pure gasoline, although NOx emissions increased moderately by 12%.
7. CFD simulations using ANSYS Fluent matched the experimental observations within 6% deviation, confirming the accuracy of the computational approach for biofuel combustion analysis.
8. Conversion of rice husk into bioethanol offers a sustainable solution for managing agricultural waste generated globally and supports renewable energy production, thereby contributing to circular economy principles and sustainable development objectives.

A. Recommendations For Industrial Scale-Up

Based on the laboratory-scale results obtained from 1 L to 10 L batches, the following conditions are suggested for pilot-scale (1000 L) and industrial-scale (100,000 L) production:

- Pretreatment: Continuous screw-feeder reactor using 4% NaOH at 90°C with 90 min residence time, followed by steam explosion at 121°C.
- Enzymatic Hydrolysis: Stirred tank bioreactor operated at 100 rpm, 50°C, pH 5.0 for 48–60 h.
- Fermentation: Co-culture fermentation in an airlift bioreactor at 30°C and pH 5.5 for 72 h.
- Distillation: Multi-effect distillation integrated with mechanical vapour recompression (MVR) to improve energy efficiency.
- Engine Application: E10 and E20 blends are suitable for conventional vehicles without modification, whereas E85 requires flex-fuel engine systems.

B. Future Research Directions

- Genetic modification of yeast strains for simultaneous saccharification and fermentation (SSF) and consolidated bioprocessing (CBP).
- Detailed life-cycle assessment (LCA) and techno-economic analysis (TEA) of rice husk-derived bioethanol.
- Conversion of lignin-rich residues into value-added materials such as biochar, activated carbon, and phenolic resin products.
- Long-term engine durability studies using bioethanol blends for more than 1000 operating hours.
- Investigation of cold-start behaviour and compatibility of engine materials with higher ethanol blends.

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Disclosure of Interests

The authors declare no conflict of interest. No competing financial or personal relationships exist that could influence the work reported in this paper.

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