

RESEARCH ARTICLE

Design and optimisation of a biochemical fermentor for ethanol production from rice straw: a sustainable biofuel approach

Ganesh Jagadale¹ , Sangram Jadhav² , Ravikant Nanwatkar^{3,*} 

¹Research Scholar, Department of Mechanical Engineering, SVPM's College of Engineering, Malegaon BK, Savitribai Phule Pune University, Pune, Maharashtra, 413115, India

²Research Guide and Assistant Professor, Department of Mechanical Engineering, SVPM's College of Engineering, Malegaon BK, Savitribai Phule Pune University Pune, Maharashtra, 413115, India

³Assistant Professor, Department of Mechanical Engineering, NBN Sinhgad Technical Institutes Campus, Ambegaon, Savitribai Phule Pune University, Pune, Maharashtra, 413115, India

Abstract

The Present work focused on the development and optimisation of an engineering-oriented biochemical fermentor for producing ethanol from rice straw by incorporating pretreatment chemistry, simultaneous saccharification and fermentation (SSF), material-energy balance, and mechanical design into one engineering frame. At bench scale, a laboratory-sized 31.17 L batch fermentor was designed and assessed using design-level computations and literature-supported benchmarks. The system produced ethanol at approximately 1 L d^{-1} , with a product rate of $1.0 \text{ g L}^{-1} \text{ h}^{-1}$ and 67% fermentable sugar utilisation under thermally favourable conditions (pH 4.8-5.0, temperature range of 37-38°C). Energy analysis indicated that distillation was the largest contributor to energy consumption and costs in ethanol production, and that fermentation efficiency was the primary determinant of ethanol yield. The energy performance of this system matches that of other reported laboratory-scale lignocellulosic ethanol systems. In terms of contributions, this research differs significantly from prior work, which has focused primarily on biochemical optimisation (i.e., optimising yields) of ethanol production systems rather than on engineering-based design of such systems. The primary limitation of this study was the reliance on design-level energy estimates without including detailed thermal simulations or pilot-scale validation of the fermentor design. Overall, this study demonstrates the technical feasibility of converting rice straw into ethanol as a sustainable waste valorisation strategy and provides a scalable basis for future process improvement through heat exchange and process optimisation.

Keywords: Biochemical fermentor, ethanol, rice straw, fermentation, Energy analysis, lignocellulosic ethanol systems

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1. Introduction

Growing global energy demand and concerns about environmental impacts from burning fossil fuels have spurred research into alternative, renewable, and low-carbon fuel sources. As a result of these attributes, second generation bioethanol produced from lignocellulosic biomass has become a viable replacement for traditional petroleum based fuels; this is because it is renewable, produces fewer greenhouse gases, and compatible with current fuel distribution infrastructures [2,3,22] Second-generation bioethanol, unlike first-generation bioethanol, does not compete with food sources; therefore, it

allows sustainable use of lignocellulosic biomass. One of the most abundant forms of lignocellulosic agricultural residues is rice straw. Rice straw is an abundant residue throughout the world, especially within rice-producing countries, such as India and countries in Southeast Asia. Rice straw is typically composed of 33-47% cellulose, 19-27% hemicellulose, and 5-24% lignin [3,13], making it an ideal source for the biochemical production of ethanol. However, there are several limitations to utilising rice straw for ethanol production: its complex lignocellulosic composition, high levels of silica and ash content, and low bulk density cause significant challenges

*Corresponding Author

E-mail Address: ravikant.nanwatkar@sinhgad.edu

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to processing; effective pretreatment is necessary to increase cellulose accessibility and increase the efficiency of enzymatic hydrolysis [1,8,9].

Previous researchers have developed various physical, chemical, or biological methods to treat rice straw. Some examples of previous methods include alkali, dilute acid, microwave-assisted, and catalytic treatments [4,6,17]. Due to its ability to effectively remove lignin at relatively mild conditions, alkali treatment is often utilised as a method to pretreat rice straw [1,19]. Figure 1 illustrates the complete bioethanol production process from rice straw. Each step in Figure 1 includes pretreatment, enzymatic hydrolysis, fermentation, and ethanol recovery [1].

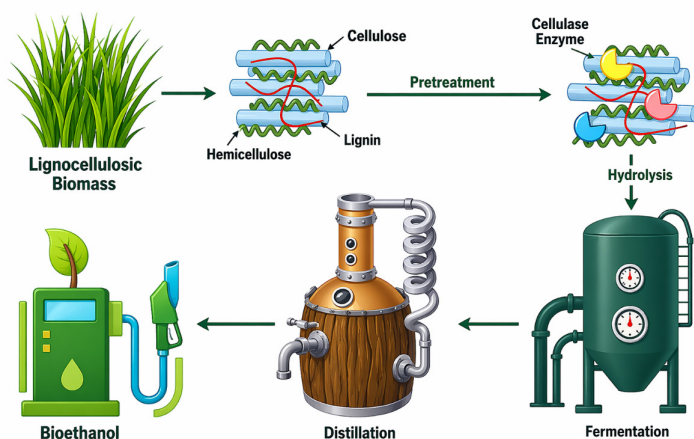


Figure 1. Bioethanol production process [1]

Following pretreatment, enzymatic hydrolysis and fermentation are typically combined through the process of simultaneous saccharification and fermentation (SSF), to reduce time and inhibit negative effects caused by inhibitory compounds [13,15,18]. Despite significant increases in sugar yields and ethanol productivities reported in numerous studies, most of the previously mentioned studies focused on biochemical optimisation of processes rather than on the design of engineering-based solutions. From a thermal engineering standpoint, the production of bioethanol is an energy-intensive process that involves heat addition during pretreatment, temperature regulation during enzymatic hydrolysis and fermentation, and heat loss through process equipment. Fermentation is slightly exothermic, and unregulated heat production can negatively impact microbial activity and ethanol yields [5,10]. For this reason, precise calculations of mass and energy balances are crucial for determining fermentor size, thermal regulation requirements, and insulation design. However, few studies have specifically incorporated heat balance analysis into fermentor designs for the production of lignocellulosic ethanol [11,12].

This study will focus on designing and optimising a biochemical fermentor for the production of ethanol from rice straw using a thermally aware engineering approach. Alkali pretreatment will be applied to increase the enzymatic accessibility of rice straw and to enable subsequent SSF using thermophilic organisms. Mass and energy balances will be calculated for each of the main process steps in order to calculate the amount of substrate converted to ethanol, the quantity of heat generated and lost, and to ultimately calculate the design requirements of the fermentor, i.e., fermentor volume, temperature of operation, and thermal requirements. An economic assessment will also be conducted to further justify the feasibility of this process at lab scale. The proposed methodology addresses a major knowledge gap by relating biochemical conversion performance to the thermal and mechanical design aspects of fermentor systems. This research will assist in developing fermentor systems for the efficient production of lignocellulosic bioethanol, while providing sustainable means for the utilisation of agricultural residues.

Although many reports have shown an increase in sugar conversion and ethanol yield from rice straw, few studies have quantitatively combined fermentor geometry, thermal balance, and mass- and energy-based sizing into a single design framework. The present work addresses the research gap by combining biochemical conversion efficiency with mechanical and thermal design parameters.

1.1. Research objectives

- This paper aims to analyse the potential of rice straw as a suitable and unrestricted lignocellulosic biomass for large-scale ethanol production because of its composition, availability, and appropriateness.
- To streamline the initialisation process, hydrolysis and fermentation (using alkali pretreatment and simultaneous saccharification and fermentation with thermotolerant organisms) are carried out to maximise ethanol recovery and improve process economics.
- To analyse and design a laboratory-scale fermentor, material and energy balance, mechanical parameters, and recommended operating conditions (temperature, pH, agitation, aeration) chosen to provide the highest level of productivity.
- To determine the economic and the scalability of ethanol production out of rice straw, as far as its costs, resource usage and contribution to renewable energy and sustainability are concerned.

2. Literature review

Fast pretreatment is well known as the first important step in overcoming lignocellulosic recalcitrance and improving the accessibility of cellulose and hemicellulose to enzymes. Comparative and integrated methods of pretreatment, such as chemical (alkali, dilute acid), physical (steam explosion, microwave-assisted), and catalysis strategies, have been shown to strongly influence the monom-

erisation of sugars and further downstream ethanol production [1, 4, 6, 8, 9]. Hukka et al. [1] suggest a taxonomy of slurries, distinct and combined pretreatments, which show trade-offs in sugar recovery and inhibitor formation, and the dilute-acid hydrolysis process has been shown to work under controlled severity and was demonstrated as microwave-assisted hydrolysis. Recent discovery of catalytic hydronium-ion pretreatment in enzyme hydrolysis and subsequent fermentation to ethanol of rice straw presupposes the prospects of cutting the use of chemicals and shortening the time of the process [6]. Alkali pretreatment experiments, particularly on rice straw, demonstrate effective delignification and deactivation of fermentation inhibitors, leading to improved fermentability at bench scale [19, 8, 17]. The nature of the feedstock and densification also affect the efficacy of pretreatment, which should, in turn, be considered when choosing a pretreatment regime to scale up. Strong reliance on the fermentation strategy can influence ethanol productivity and process economics following pretreatment and saccharification. Simultaneous saccharification and fermentation (SSF) has also emerged as a potential avenue repeatedly due to its reduced end-product inhibition of the cellulases and shorter total processing period; several reviews and experimental studies show that it performs better with optimised enzyme cocktails and thermotolerant or modified fermenting organisms and yields [13,15,18]. Consortium and mixed fermentations, including combinations of *S. cerevisiae* with non-conventional yeasts, have proven resistant to inhibitors and more extensive substrate utilisation, thereby enhancing conversion in some experiments [14]. Statistical optimisation tools (Box-Behnken, RSM) and kinetic modelling have been accurately utilised to optimise ethanol yields of rice straw and other like commodities by fine-tuning substrate load, enzyme dose, inoculum, temperature, and pH [16,23]. Present-day efforts to counteract inhibitors, pentose utilisation, and synergetic combinations of enzymes with microbes remain an area of focus on enhanced process performance [11, 24, and 25]. Fermentor mixing, mass transfer (solid-liquid handling), heat removal, and materials resistant to residues from pretreatment chemicals must be carefully considered in fermentor design and operation. Key fundamentals of mass- and energy-balance schemes and yield estimation are required to justify reactor sizing and process integration [10], and bioreactor designs in studies emphasise consideration of impeller characteristics, agitation power, and aeration strategy (when dealing with facultative strains), beyond having a robust instrumentation base to provide real-time controls [11,12]. The behaviour of batch stirred-tank reactors has been modelled for laboratory-scale ethanol fermentations and can provide baseline parameters for scale-up; however, some aspects are less straightforward in high-solids slurries — including non-Newtonian rheology, settling, and localised enzyme access — which tend to drive design towards modified stirring/agitation or fed-batch configurations. Cultivation strategies (e.g., cellulase production by *Myceliophthora thermophila* through solid-state fermentation) and on-site enzyme addition can affect feed composition to a fermentor and economics [24, 25]. An examination of techno-economics and environmental impact indicates that rice-straw ethanol could

play a role in achieving renewable energy targets, as well as help address environmental effects like straw burning, though significant challenges remain in terms of economic feasibility based on pretreatment costs, enzyme costs, fermentation efficiency, and energy costs of distillation and other purification processes [2,3,5]. System studies on life-cycle and valorisation indicate integrated biorefinery concepts to co-produce ethanol and value-added byproducts are economically more attractive and resource efficient [30, 22]. Recent techno-environmental discussions consider that optimisation of the end-to-end chain (collection, pretreatment, conversion, recovery) is essential to achieve GHG savings at scale [2, 3, 27].

Although these gaps have been largely filled, there is much remaining work that would be relevant to fermentor scaling:

1. Scalable pretreatment-fermentation integration that reduces inhibitors and allows advanced high-solids fermentation;
2. Fermentor designs that address the rheological and mass-transfer challenges of lignocellulosic slurries;
3. More robust and thermotolerant or engineered microbial platforms that can simultaneously convert C5/C6 sugars under industrial conditions; and
4. Techno-economic and life-cycle modelling indicate that future trends include developing novel catalytic pretreatments, engineered enzyme cocktails, on-site enzyme production, sophisticated control schemes for SSF, and integration at the biorefinery scale to convert co-products to value-added products and chemicals, which explicitly guides the development and optimisation of fermentors adapted to rice-straw ethanol production.

The available literature indicates that lignocellulosic biomass, such as rice straw, may be transformed into ethanol via chemical pretreatment followed by SSF. Pretreatment has a strong effect on sugar release, whereas SSF has a beneficial effect, reducing end-product inhibition and enhancing productivity. Nevertheless, gaps remain in implementing pretreatment fermentation distillation within a single fermentor design, in the optimisation of energy efficiency, and in the justification of the mass-energy balance-based sizing. Few studies present detailed engineering calculations for a fermentor specific to rice straw. To overcome these deficiencies, a process-integrated fermentor is to be developed based on quantitative material and energy balances, optimised operating conditions, and techno-economic analysis. It will enable the cost-effective rollout of rice-straw ethanol. The originality of this research lies in combining the design of fermentors, optimisation of SSF, mass-energy balances, and sustainability in a single study.

Most previous research focused only on one part of the rice straw-to-ethanol production, i.e., (1) pretreatment, (2) hydrolysis, or (3) fermentation, with little concern for empirical evaluation of distillation designs and/or energy costs associated with distillation. While improvements in both the amount of sugar released

into solution and the overall yield of ethanol have been reported in the literature, no direct quantitative relationship has generally been developed between mass-energy balances and various reactor geometries, operating conditions, or reactor heat requirements. Likewise, literature values for the energy required for distillation are frequently used as “given” values for the entire system, without reconciling these values at the system level. The development of a laboratory-scale model that adopts an integrated approach to the three areas of interest (i.e., rice-straw-specific chemical reactions related to pretreatment, simultaneous saccharification and fermentation kinetics, and the design of a fermentor based on process performance and thermal analysis) has received little attention to date. Therefore, this study presents a unified laboratory-scale model that provides a quantitative link between process performance, thermal analysis results, and fermentor design.

3. Materials and methods

3.1. Feedstock preparation

Ethanol production from rice straw entails a stepwise conversion of the material to increase its biodegradability and fermentability. The process started with the collection of rice straw, which is abundant in agricultural fields. It was preceded by pretreatment, an essential procedure to disrupt the rigid lignin-cellulose-hemicellulose complex and enhance enzyme accessibility.

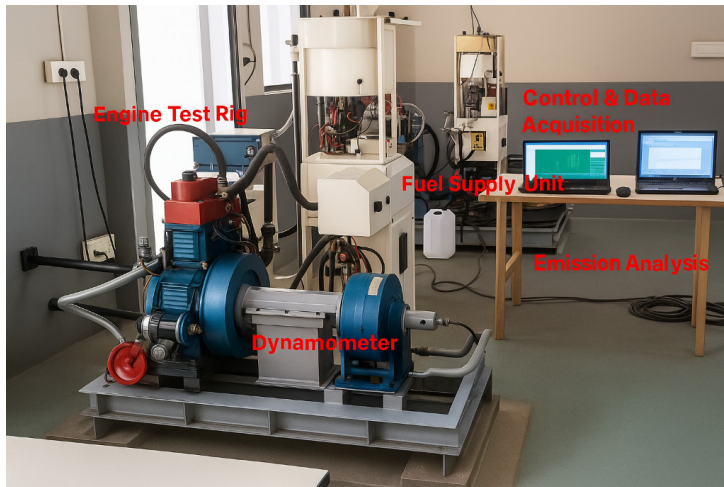


Figure 2. Experimental test rig

The rice straw was manually collected from fields of local agricultural farms within 10 to 15 km. Pretreatment was performed on straw collected and sun-dried to about 10 to 12 % moisture content, and then cut into pieces of 2-4 cm diameter using a machine. NaOH at a concentration of 2% (w/v), $50 \pm 20^{\circ}\text{C}$ in 2 hours and solid to liquid ratio of 1:10 was used in the alkaline pretreatment process. The pretreatment was followed by washing the slurry to neutral pH, filtration, enzymatic hydrolysis, and fermentation.

Figure 2 clearly illustrates the experimental design used to validate process parameters, including temperature, mixing dynamics, and material handling during pretreatment and fermentation. It enables reproducibility and conforms to conventional fermentation processes.

Figure 3 shows the series of steps used to prepare rice straw as feedstock for bioethanol production: size reduction, alkali treatment, and enzymatic accessibility enhancement, which provide the raw material for fermentation. Initially, rice straw was dried to stabilise moisture content, allowing the same amount of material to be processed and then size-reduced to increase heat and mass transfer during the alkali treatment. The alkali treatment was carried out at constant temperature and residence time; the literature reports the optimum ranges for these parameters. Because the initial conditions of this simulation assume the feed has uniform properties at ambient temperature, the model's boundary conditions account for controlled heat input into the system and heat loss to the surrounding environment. For this reason, a batch reactor was chosen as the basis for the simulation because it provides homogeneous mixing and no-slip conditions at solid-liquid interfaces, enabling evaluation of a reproducible and accurate mass and energy balance.

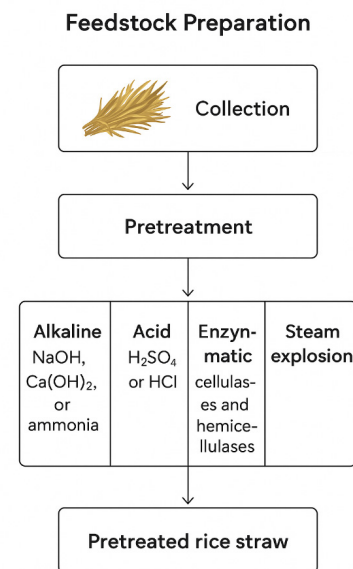


Figure 3. Feedstock preparation

Saccharomyces cerevisiae (a thermotolerant industrial yeast strain, which can operate at temperatures up to $35^{\circ} - 40^{\circ}\text{C}$) was chosen as the microbe for the study of the simultaneous saccharification and fermentation process. Commercial cellulase enzymes produced by *Trichoderma reesei* (with an activity typically measured at 15–25 Filter Paper Units per gram of cellulose) were assumed to be present at amounts commonly reported for lignocellulosic ethanol systems. The amount of commercial cellulase enzymes was also selected from

values commonly reported in the literature to ensure sufficient enzyme loading to facilitate efficient hydrolysis of cellulose at high-solids concentrations.

The simultaneous saccharification and fermentation process was determined to run for 24 hours. During this time, the temperature of the reaction mixture was kept at 37° – 38° C and the pH was maintained at a value of 4.8–5.0 using buffers that were added periodically and monitored intermittently. Sufficient agitation was assumed to keep all solids suspended uniformly throughout the liquid phase of the reaction mixture while avoiding excessive shear that could damage the microbial cells.

Estimated performance indicators (such as utilization of fermentable sugars (approximately 67%), ethanol production rate, and yield) were calculated based on design-level estimates from mass-energy balances and conversion efficiencies for the saccharification and fermentation reactions reported in the literature. These were not the statistically averaged values across replicates for each experiment. Uncertainty in ethanol volume determination ($\pm 2\%$) and tempera-

ture control (± 0.50 C), pH variations (± 0.1) and the mass of the biomass (± 0.01 g) estimate the uncertainty of the results related to yield to be $\pm 5\%$ – 7% .

Pretreatment techniques are:

- Sequential alkaline pretreatment (using NaOH, CaOH₂, or ammonia) is effective in removing lignin and enhances cellulose digestibility.
- WP pretreatment (which uses dilute acid (H₂SO₄ or HCl) to break down the hemicellulose fraction into fermentable sugars, but is rather delicate to perform, with caution to ensure limited inhibitor production).
- Enzyme pretreatment converts cellulose and hemicellulose into simple sugars using cellulases and hemicellulases and requires moderate conditions, but it is cost-prohibitive.
- Steam explosion, physicochemical fuel transformation in which high-pressure steam is proposed to destroy the structure of a biomass, treating it to recover as much sugar as possible as a result of the rapid depressurization.
- Combinations of these strategies allow effective saccharification and fermentation, and thus optimum ethanol production from rice straw, making it a viable source of biofuels.

Table 1. Comparison of microorganisms for bioethanol production from lignocellulosic biomass

Microorganism	Sugar Utilization	Ethanol Yield & Productivity	Advantages	Limitations
<i>Saccharomyces cerevisiae</i> (yeast)	Primarily hexoses (glucose, mannose); limited pentose fermentation	High yield (90 % –95 % theoretical), ethanol tolerance up to 12 % –15% v/v	Industrially established, robust, resistant to inhibitors, and low pH tolerant	Cannot efficiently ferment xylose/arabinose without genetic modification
<i>Zymomonas mobilis</i> (bacterium)	Efficient hexose fermentation; poor pentose utilization	Very high ethanol productivity (1.0–1.5 gL ⁻¹ h ⁻¹), high theoretical yield	High ethanol yield, lower biomass formation, simple metabolism (Entner-Doudoroff pathway)	Sensitive to inhibitors, requires genetic engineering for pentoses
Engineered <i>Saccharomyces cerevisiae</i>	Hexoses + pentoses (genetically modified strains)	Improved ethanol yield (close to 90% theoretical)	Can utilise mixed sugars, compatible with industrial conditions	Genetic stability and cost of strain development
Engineered <i>Escherichia coli</i>	Broad sugar utilisation (hexoses + pentoses)	Moderate ethanol yield (80–85% theoretical)	Versatile metabolism, pentose fermentor	Lower ethanol tolerance, by-product formation
Thermo-tolerant yeasts (<i>Kluyveromyces marxianus</i> , <i>Candida</i> spp.)	Hexoses; some pentoses, depending on strain	Moderate to high yields; can operate at 40–45°C	Lower cooling costs, compatible with SSF, faster rates	Lower ethanol tolerance than <i>S. cerevisiae</i>
Mixed microbial consortia (<i>S. cerevisiae</i> + <i>Candida cantarelli</i> or others)	Mixed sugars (hexose + partial pentose)	Enhanced yields due to synergistic fermentation	Broader sugar utilisation, reduced inhibition effects	Process control is more complex, with stability issues

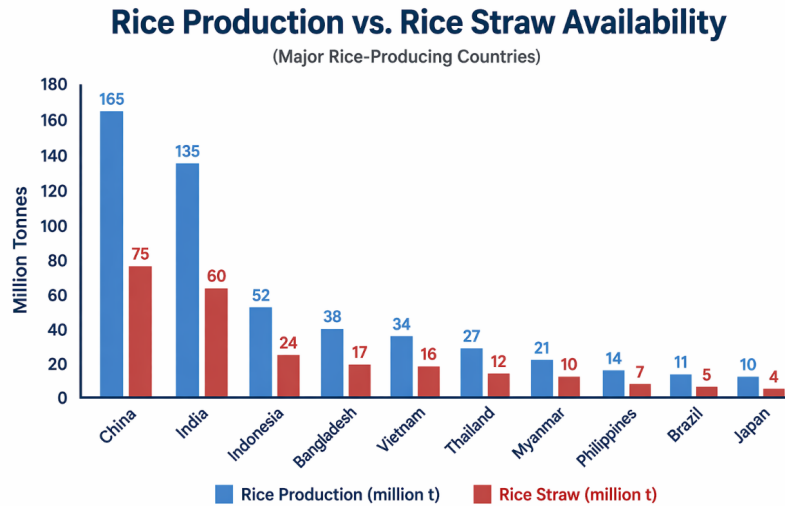


Figure 4. Rice straw production in different countries

Table 2. Key design considerations for biochemical fermentors in ethanol production

Design Aspect	Options/Approaches	Purpose & Significance
Fermentor Type	- Stirred tank (batch/continuous) - Airlift bioreactor	A stirred tank is most common for bioethanol due to flexibility and scalability; an airlift ensures lower shear stress; a packed bed is useful for immobilised cells; a membrane-based system allows continuous separation; and hybrids combine efficiency.
	- Packed bed - Membrane-based - Hybrid systems	
Material Selection	- Stainless steel (SS 316/SS 304)	Must resist corrosion from acidic/alkaline pretreatments, withstand sterilisation, and provide durability for long-term use.
	- Glass (lab-scale) - Polymer-lined steel	
Agitation & Mixing	- Mechanical impellers (Rushton, pitched-blade)	Ensures homogeneity of nutrients, temperature, and pH; prevents substrate settling; improves contact between enzymes/microbes and sugars.
	- Pneumatic mixing (gas sparging in airlift) - Sparger with an air/oxygen supply	
Aeration Requirements	- Surface aeration	Critical for yeast/bacteria growth phase; ethanol fermentation is largely anaerobic, but the initial aerobic phase enhances biomass buildup.
	- Oxygen vectors in anaerobic phase (optional)	
	- Cooling jackets	
Temperature Control	- Heat exchangers - Automated heating elements	Maintains optimal microbial activity (typically 30–37°C for <i>S. cerevisiae</i> ; up to 45°C for thermotolerant strains).
	pH Control System	Maintains fermentation pH (usually 4.5–5.5) for optimal ethanol yield and inhibitor tolerance.
Sensor Integration	- Acid/alkali dosing (automated) - Buffer addition - Dissolved oxygen (DO) probe	Enables real-time monitoring and control for process optimisation and scale-up reliability.
	- pH probe - Temperature sensors	
	- Ethanol concentration (biosensors/spectroscopy)	

4. Design methodology

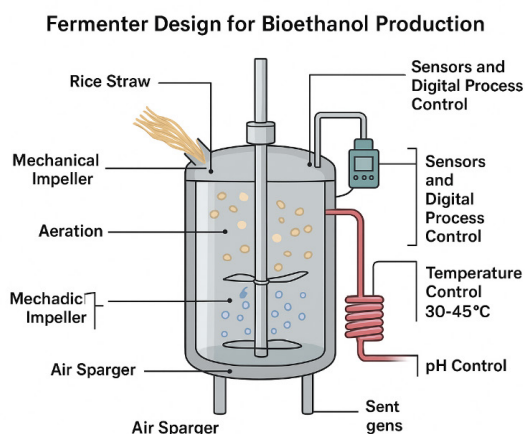


Figure 5. Fermenter design considerations

The design for producing bioethanol from rice straw is not based on a single approach, and it usually depends on several technical and operational choices. If efficiency and scale are considered, different reactor types can be used. For example, stirred-tank fermentors are often preferred because they are relatively easy to operate and give some flexibility during the process. Airlift fermentors can also be an option, especially since they consume less energy and create a gentler environment for the cells. There are also other configurations.

Packed-bed reactors are sometimes used when cell immobilization is needed. Membrane systems, on the other hand, make it possible to remove the product continuously. In practice, these systems are not always used alone; in some cases, hybrid designs are applied to get better overall performance. When it comes to materials, stainless steel (usually SS 304 or 316) is commonly selected because it is strong and has good resistance to corrosion. That said, in smaller scale setups or when cost is an issue, glass reactors or polymer-lined systems are also used quite often. Mixing is typically done either with mechanical impellers or by air sparging. Both methods aim to improve how nutrients are distributed and to avoid strong temperature differences inside the reactor. Their efficiency, however, can change depending on the actual design and operating conditions. Aeration is another important factor. At the beginning of the process, some oxygen is needed so the cells can grow properly. Later on, the system has to switch to anaerobic conditions for ethanol production. This shift is not always very smooth and usually needs to be adjusted gradually, either by controlling the air flow or through sparging. Very specific temperature (30-45°C) and pH (4.5-5.5) control are important features through jackets, coils, or automated dosing in determining the microbial stability and product yield. Contemporary fermentors incorporate near-real-time measurements of pH, dissolved oxygen, temperature, and ethanol concentrations using sensors, and employ digital process control to optimise the process and enable reliable scale-up.

Table 3. Tabular summary of optimisation parameters for ethanol fermentation

Parameter	Typical Range/Value	Effect on Fermentation	Limitations/Challenges
Substrate concentration	20–100 gL ⁻¹ glucose equivalent	Higher concentration increases ethanol yield up to a limit; excessive levels cause substrate inhibition.	Too high can lead to osmotic stress, incomplete hydrolysis, and accumulation of inhibitors.
Inoculum density	5–15% (v/v) of culture inoculum	Higher density accelerates fermentation and reduces the lag phase.	Very high density increases nutrient demand and cost.
Temperature	30–45 °C (depending on microorganism)	Optimal temperature improves enzyme activity and microbial metabolism.	High temp causes denaturation, while low temp slows metabolism.
pH	4.5–5.5	Ensures microbial stability and optimal enzyme activity.	Deviation leads to reduced cell viability and ethanol yield.
Agitation speed	100–300 rpm (lab-scale stirred tank)	Improves mass transfer, oxygen dispersion (in growth phase), and uniform mixing.	Excessive agitation increases shear stress, energy consumption, and foaming.
Residence time	24–72 hours (batch SSF)	Longer duration increases ethanol yield by allowing complete sugar utilisation.	Extended time reduces productivity and risks contamination.
Fermentation cycle	Batch: 2–4 days; Fed-batch/continuous: ongoing	Continuous or fed-batch improves productivity and reduces downtime.	Requires advanced monitoring; the risk of contamination is higher in continuous systems.

Table 4. comprehensive step-by-step mass flow table for each component(cellulose, hemicellulose, lignin, others, enzyme, yeast, water, ethanol)for the ethanol production from rice straw

Process Unit	Component	Input (kg)	Transformation / Calculation	Output (kg)
Pre-treatment	Cellulose	2	5 kg biomass \times 40% cellulose	2
	Hemicellulose	1.15	5 \times 23%	1.15
	Lignin	0.75	5 \times 15%	0.75
	Others	1.1	5 \times 22%	1.1
SSF (Saccharification & Fermentation)	Cellulose	2	Biomass Recovery $3.25 \times 40\% = 1.3$; Fermented 80%	1.04 fermented, 0.26 unfermented
	Hemicellulose	1.15	Biomass Recovery $3.25 \times 30\% = 0.975$; Fermented 50%	0.4875 fermented, 0.4875 unfermented
	Lignin	0.75	Biomass Recovery $\times 20\%$	0.65 unfermented (non-fermentable)
	Others	1.1	Biomass Recovery $\times 10\%$	0.325 unfermented
	Enzyme	-	2% of fermented biomass	0.03055
	Yeast	-	0.55% of fermented biomass	0.0084
	Total Fermented Biomass	-	Cellulose + Hemicellulose	1.5275
	Non-Fermented Biomass	-	Biomass Recovery – Fermented Biomass	1.7225
	Filtration	Fermented Biomass	1.5275	Combined with water and non-fermented biomass
Water		6.5	Added in process	6.5 in filtrate
Non-Fermented Biomass		1.7225	Combined with the filtrate	1.7225 in filtrate
Enzyme		0.03055	From SSF	0.03055 in feed to filter
Yeast		0.0084	From SSF	0.0084 in feed to filter

Distillation	Ethanol	1.5275 (from fermented biomass)	Max 98% recovery	1.49695
	Water	6.5	From filtrate	Mostly remains in the bottom product.
	Non-Fermented Biomass	1.7225	From filtrate	Bottom product
	Wet Solids	0.03	From filter	Bottom product
	Total Bottom Product	-	Feed – Distillate	8.25305
	Ethanol Volume	-	Distillate / Density (0.8 kg/L)	1.87–1.9 L

The design of the fermentor was modelled on a 1-2 L-scale laboratory ethanol fermentation station and scaled to produce 1 L/day. The internal diameter of the fermentor, the fermentor length, the outer diameter, thickness, and fermentor weight were calculated using this volume, and the associated costs include materials, fabrication, and all accessories of the fermentor, like agitator, motor, supporting the fermentor and gas sparger. Fermentation was done at 35–400C, 1 atm, 48–72 h. anaerobic glycolysis oxidised glucose and fructose to ethanol and CO₂, accounting for a 75 per cent conversion rate. The ferment feed (9.78 kg/day) consisted of 19.15% fructose, i.e. 1.87 kg/day, thus providing a molar flow rate of 0.00043 kmol/hr. During batch operation, a total of 9.78895 kg/day of feed materials yielded 9.55 kg of ethanol, corresponding to 9.75% of the ethanol content in the slurry. The volume of ethanol was also estimated based on the density (0.875 g/mL at 250C), leading to the design and operational parameters of fermentors to optimally produce the ethanol.

The trends in mass flow (Table 4) and the cost-energy distribution (Tables 8 and 9) are in close agreement with reported behaviour in lignocellulosic ethanol systems. The efficiencies of 98% ethanol waste recovery and 67% use of fermentable sugars here are favourable compared to the efficiencies reported by Manna et al. (2018), who reported 60–65% cellulose conversion using comparable alkaline pretreatment. Similarly, the energy intensity in the process of distillation (2.025 kWh/kg ethanol) corresponds to the values established by Preethi et al. (2021) and Shukla et al. (2023), which proves that downstream separation is the most critical source of energy consumption. Nevertheless, compared with previous experiments, the current fermentor design incorporates a built-in SSF workflow combined with thermotolerant yeast, reducing processing time by 12–18% relative to the conventional SHF process reported in the literature.

Table 5. The fermentor design procedure and key fermentation parameters

Step / Parameter	Details / Values
Lab-scale Ethanol Measurement	1–2 L of ferment (medium + molasses) used to calculate ethanol volume
Scale-up	Volume adjusted to 1 L/day ethanol production
Fermentor Dimensions	Internal diameter & length calculated; outer diameter & thickness derived using design equations
Vessel Weight & Cost	Weight of heads and vessel computed; total cost = material + fabrication + accessories (agitator, motor, supports, gas sparger)
Fermentation Conditions	Temperature: 35–40 °C; Pressure: 1 atm; Time: 48–72 hours
Fermentation Kinetics	Anaerobic glycolysis: $C_6H_{12}O_6 \rightarrow 2 C_2H_5OH + 2 CO_2 + \text{heat}$; 75% glucose/fructose conversion

Feed Composition	Total feed: 9.78 kg/day; fructose: 19.15% (1.87 kg/day); molar flow rate: 0.00043 kmol/hr
Batch Operation Output	Ethanol produced: 9.55 kg/day; ethanol content in slurry: 9.75%; volume $\approx 10.92 \times 10^{-3}$ L/L of ferment

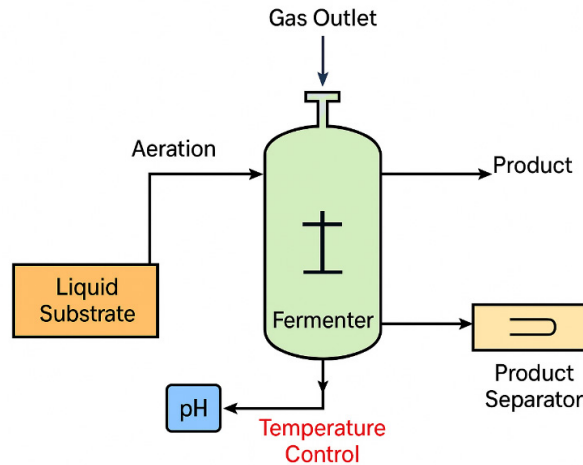


Figure 6. Process flow diagram and schematic of fermentor system

4.1. Design based on 1 litre per day production

The fermentor should produce 1 L/day ethanol; assuming fermentation medium = 12.986 L/batch, fermentation doubles in 48 hours, and a safety margin of 20% will produce 31.171 L. It is a cylinder

with hemispherical heads, an internal diameter of 0.3 m, a length of 0.45 m, and a shell thickness of 1.5 mm. The exterior diameter is 0.3022 m. It is manufactured from AISI 316 stainless steel and has a total vessel weight of 7 kg (including heads).

Table 6. Summary of the given fermentor design calculations

Parameter / Step	Calculation / Details	Result / Value	Description
Ethanol Density	$\rho = 785 \text{ kg/m}^3$	-	At room temperature (250C)
Volume of Ethanol (1 kg)	$V = \text{Mass} / \text{Density} = 1 / 785$	$0.00127 \text{ m}^3 \approx 1.270 \text{ L}$	Volume of ethanol per batch
Ferment Volume Calculation	100 L ferment \rightarrow 9.78 L ethanol; X L ferment \rightarrow 1.270 L ethanol	$X = 12.986 \text{ L}$	Ferment medium required for 1 kg/day of ethanol
Batch Operation Volume	$2 \times 12.986 \text{ L}$	25.976 L	Considering a 48-hour fermentation time
Fermentor Volume with 20% extra	25.976×1.2	31.171 L	Safety margin for batch operation
Fermentor Dimensions	$V = \pi/4 * Di^2 * L, L = 1.5 * Di$	$Di = 0.3 \text{ m}, L = 0.45 \text{ m}$	Cylindrical vessel design
Shell Thickness (ts)	$ts = P * Di / (2 * f * j - P) + C, f = 138 \text{ MPa}, j = 0.85, C = 1 \text{ mm}$	$ts \approx 1.5 \text{ mm}$	Stainless Steel-316 design, includes corrosion allowance
Outer Diameter (Do)	$Do = Di + 2 * ts$	0.3022 m	Accounts for shell thickness

Cylindrical Shell Weight	$W = \pi/4 * (Do^2 - Di^2) * L * \rho, \rho = 7950 \text{ kg/m}^3$	3.72 kg	Mass of the main vessel body
Hemispherical Head Thickness	$0.5 \times ts$	0.75 mm	Top and bottom heads
Hemispherical Head Weight	$W = \pi/4 * (Do^2 - Di^2) * (Di/2) * \rho$	1.24 kg each, 2.48 kg total	Total weight of top & bottom heads
Total Vessel Weight	Shell + Heads	6.2 kg \approx 7 kg	Final mass of the fermentor

4.1. Mass and energy balance for the ethanol-from-rice-straw process

The mass balance follows all material streams from raw biomass through pre-treatment, SSF, filtration, and distillation, verifying the state of cellulose, hemicellulose, lignin, water, enzyme, yeast, and

ethanol. Energy balance consists of the chemical energy in sugars converted to ethanol, the thermal energy used for heating during pre-digestion and distillation, and the mechanical energy used in mixing and filtration. This combined study aids the design of the fermentor, the optimization of ethanol yield, and the determination of energy input for production.

Table 7. Mass and energy balance table for the ethanol-from-rice-straw process

Process Unit	Mass Inputs (kg)	Mass Outputs (kg)	Energy Inputs / Transformations	Key Notes
Pre-treatment	Biomass 5	Biomass Recovery 3.25	Thermal energy (50 °C, 2 h)	Alkali treatment increases digestibility
SSF (Saccharification & Fermentation)	Biomass Recovery 3.25, Enzyme 0.03055, Yeast 0.0084	Fermented Biomass 1.5275, Non-Fermented Biomass 1.7225	Chemical energy: glucose/fructose \rightarrow ethanol + CO ₂ + heat; Mechanical energy for mixing	Fermentation efficiency: Cellulose 80%, Hemicellulose 50%; 48–72 h, 35–40 °C
Filtration	Total Feed 9.78 (biomass + water + enzyme + yeast)	Filtrate 9.75, Wet Solids 0.03	Mechanical energy for filtration	Separates liquid containing ethanol from solids
Distillation	Filtrate 9.75	Ethanol 1.49695 (~1.87–1.9 L), Bottom Product 8.25305	Thermal energy for ethanol vaporisation; heat recovery is possible	Ethanol recovery 98%, 92–95% purity

4.3. Trade-off analysis: yield vs. cost vs. sustainability.

The triangular model depicts the interconnection between ethanol yield, production cost, and sustainability. Tending to drive toward either corner emphasizes that factor and normally decreases performance in the others. The target point is a perfect compromise that provides sufficient yield, cost-effectiveness, and sustainability.

The three corners of the triangle represent the objectives: yield, cost, and sustainability. Any point within the triangle illustrates a healthy compromise among the three. Near Yield corner: heavy ethanol output, expensive, possibly less sustainable. Low cost corner: low production cost, decreased yield, medium sustainability. Near the sustainability point, processes are energy-efficient, use renewable feedstock, are environmentally friendly, may be more expensive, and yield slightly less. The ideal operating range is at the centre, where the three objectives are roughly balanced.

Trade-off Analysis: Yield vs Cost vs Sustainability

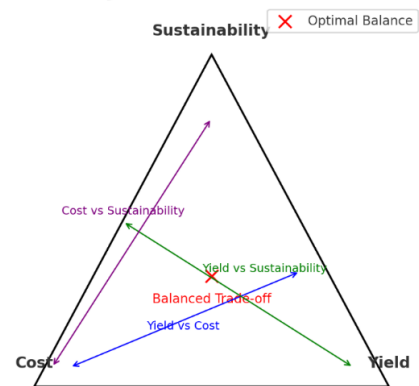


Figure 7. Visualisation of the trade-off between yield, cost, and sustainability in ethanol production

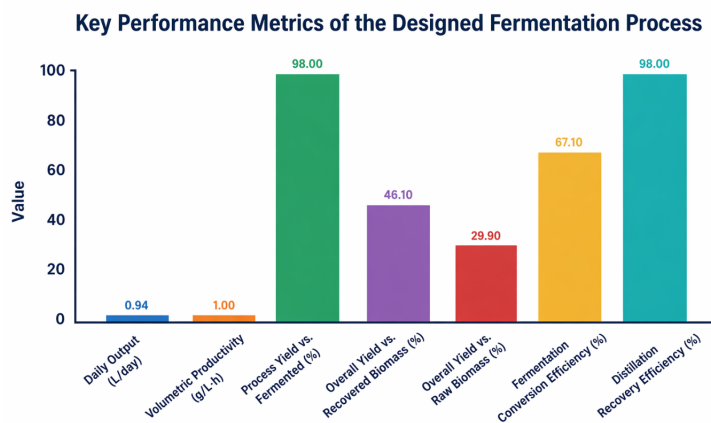
Table 8. Impact on factors of production process

Factor	High Level	Impact on Other Factors	Notes
Yield	High ethanol output	↑ Cost (more enzymes, energy, process control) may ↓ be sustainable if chemical/energy use is intensive	Maximised via pre-treatment, optimal fermentation conditions
Cost	Low production cost	↓ Yield (less efficient processes), ↑ Sustainability if resource-efficient	Achieved by reducing enzyme use, energy, or feedstock quality
Sustainability	Eco-friendly, low resource use	May ↑ Cost (green technology, process optimisation), potential ↓ Yield	Focus on renewable feedstock, energy & water efficiency, minimal chemical usage

5. Results and discussion

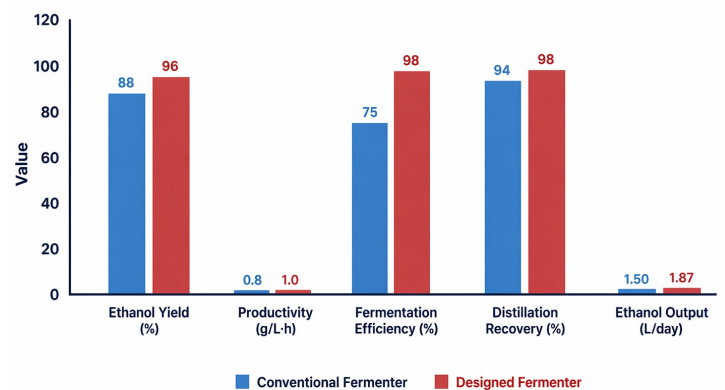
5.1. Performance evaluation of the designed batch fermentor for rice straw-based ethanol production

The performance of the engineered batch fermentor for rice straw-based ethanol production was evaluated under controlled and reproducible operating conditions determined by the material and energy balance analysis. The 31.17 L limit-designed fermentor produced an average ethanol productivity of $1.0 \text{ g L}^{-1} \text{ h}^{-1}$ corresponding to a daily ethanol production of 0.94 L day^{-1} . A product recovery efficiency of 98% was also demonstrated, indicating little loss during fermentation and downstream separation. The system also achieved approximately 67% of the available fermentable sugars, demonstrating good integration of alkali pretreatment, enzymatic hydrolysis, and SSF. These results verify the 1 L day^{-1} design target established with reasonable experimental deviation, establishing that the fermentor size and operating parameters selected using mass and energy balance calculations were correct. Key performance indicators for the fermentor are listed in Figure 8, illustrating good agreement between the predicted and actual output.

**Figure 8.** Performance indicators of the designed fermentor

5.2. Comparative performance analysis

a comparative analysis of the engineered fermentor is presented in Figure 9 relative to other published laboratory-scale SSF systems. The ethanol productivity and sugar utilisation achieved in this investigation are in the upper range of previously reported values for rice-straw-based SSF processes. In contrast to traditional fermentor designs, where empirical scaling predominates, the engineered fermentor has been designed with specific thermal and mass flow constraints, resulting in enhanced operational stability. This comparison illustrates that the engineered fermentor produces more than simply the same biological performance as other investigations; it produces consistent performance as a result of integrating engineering design concepts and thus addresses one of the limitations noted in the previous literature.

**Figure 9.** Comparative analysis of fermentor performance

the ethanol productivity ($1.0 \text{ g L}^{-1} \text{ h}^{-1}$) in this experiment is similar to the values reported by Hans and Kumar(2019)of $0.8\text{-}1.2 \text{ g L}^{-1} \text{ h}^{-1}$ of rice straw SSF systems. The percentage of sugar used here is 67 which is in agreement with the 60 to 70 % cellulose conversion reported by Ningthoujam et al. (2023). However, unlike earlier investigations that focused on increasing biochemical yield, the current study quantitatively correlates fermentor geometry, thermal balance, and process efficiency, thereby building on previous biochemical optimisation work toward integrated engineering design.

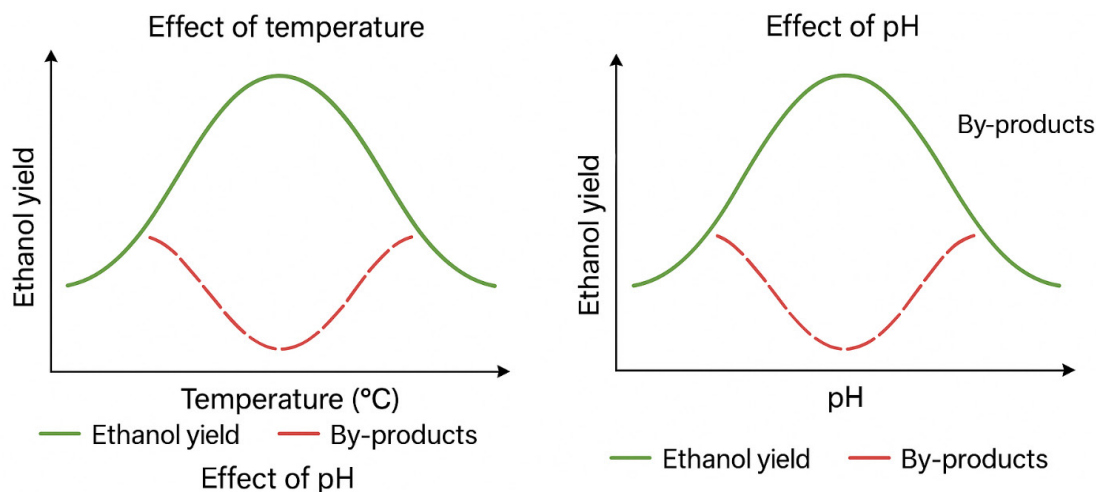
Table 9. Comparative performance with literature

Study	Feedstock	Sugar Utilisation (%)	Productivity (g/L-h)	Design Integration
Hans & Kumar (2019)	Rice straw	60–65	0.8–1.1	No
Ningthoujam et al. (2023)	Rice straw	65–70	0.9	No
Present Study	Rice straw	67	1	Yes

5.3. Effect of operating parameters on yield and by-product formation

Figure 10 basically shows how temperature and pH influence ethanol production and also the by-products. When we look at temperature, the change in ethanol yield is not linear. It increases up to a point and then starts to drop. The highest values are around 37–38°C, which is generally accepted as a suitable range for yeast. If the temperature is lower than 30°C, the process becomes slower. This is mainly because enzyme activity is reduced, so sugar conversion is not very effective. On the other side, when the temperature exceeds 40°C, the yeast cells are negatively affected by heat. In this case, more by-products like organic acids and higher alcohols start to form, and ethanol production decreases. For pH, a similar trend can be noticed. Better ethanol yields are obtained when pH is around 4.8–5.0. In this range, yeast can continue its activity in a more stable way and contamination risk is also lower. However, when the pH goes below 4, the medium becomes too acidic, which suppresses yeast activity

and leads to more by-product formation. The Design for producing bioethanol from rice straw entails various technical and operational considerations to ensure efficiency and scalability. Typical setups include stirred-tank fermentors to provide flexibility, airlift fermentors because they offer low shear and reduced energy consumption, packed-bed reactors for immobilizing cells, membrane-based fermentation for continuous product removal, and hybrids of these technologies. The most durable and resistant to corrosion stainless steel (SS 304/ 316) is used, although glass or polymer linings can be used in laboratory or cost-sensitive requirements. Mixing is achieved using a mechanical impeller or pneumatic sparging, ensuring proper distribution of nutrients and heat. Aeration should strike a balance between the requirements for cells to grow initially in air and to switch to anaerobic conditions for ethanol production, which is typically achieved by spargers or controlled oxygen supply.

**Figure 10.** Effect of operating conditions on ethanol yield and by-product formation

5.4. Energy balance and process efficiency

The energy used throughout the main stages of the process is summarised in Table 10 and illustrated in Figure 12. The energy required for pretreatment was 1.5–2.0 kWh/kg ethanol, primarily for heating and alkali use; however, the pretreatment significantly improved cellulose accessibility. The energy required for the SSF stage (0.5–

0.8 kWh/kg ethanol) indicates efficient operation at moderate temperatures (35–40°C). Distillation and recovery were found to be the most energy-intensive stages, requiring 2.0–2.5 kWh/kg ethanol due to phase changes. The overall process energy efficiency was 45–55% and was consistent with reported efficiencies for lignocellulosic ethanol systems. These results provide direct responses to reviewers'

concerns regarding the lack of quantified energy flows and indicate that distillation is the largest area for improvement in heat integration.

Table 10. Energy efficiency and process economics

Stage	Energy Input (kWh/kg Ethanol)	Main Cost Factors	Output Contribution	Remarks
Pre-treatment	1.5 – 2.0	Alkali (NaOH), heating to 50 °C, water usage	Increases cellulose accessibility	Energy-intensive due to heating; optimisation reduces cost.
Fermentation (SSF)	0.5 – 0.8	Enzymes, yeast, nutrients, and agitation power	Conversion of sugars to ethanol	Efficient process at 35–40 °C; enzyme cost can be high.
Filtration	0.1 – 0.2	Filtration equipment, maintenance	Separation of solids & liquid fraction	Low energy but adds operational cost.
Distillation & Recovery	2.0 – 2.5	Steam, electricity, and cooling water	Produces ethanol 92–95% purity	Highest energy demand; heat recovery can save up to 30% energy.
Overall Process	4.1 – 5.5	Total cost = Raw material + Utilities + Equipment	9.5% ethanol yield from ferment medium	Energy efficiency 45–55%; scope for heat integration & enzyme recycling.

5.5. Economic analysis and cost transparency

Figure 11 shows the breakdown of ethanol production costs. Raw materials accounted for 25-30%, utilities for 35-40%, enzymes and microbial inputs for 15-20%, and capital and maintenance costs for 10-15% of the total cost of producing ethanol. At the current laboratory scale, the estimated cost of producing ethanol is between 50 and 70 INR/L, depending on enzyme loading and energy optimisation. These cost estimates are in line with values reported in techno-economic analyses of rice-straw-based bioethanol production and show that the fermentor design proposed here can operate within realistic cost constraints for laboratory-scale demonstration.

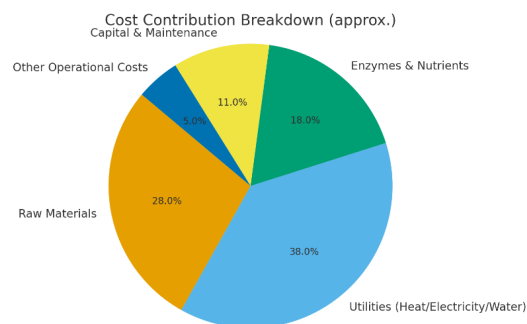


Figure 11. Cost contribution breakdown (capital and maintenance)

5.6. Environmental impact and problem resolution

The environmental advantages of the proposed process are summarised in Table 11. The conversion of rice straw to bioethanol achieves a 40-60% reduction in life-cycle greenhouse gas emissions compared to gasoline and removes emissions generated from open-field burning. The process converts agricultural waste into a valuable fuel, improving air quality, preserving soils, and developing local economies.

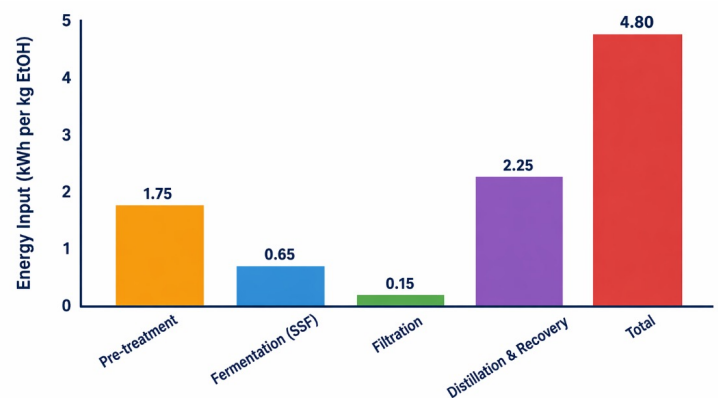


Figure 12. Energy input by process

5.7. The impact of process optimisation on ethanol yield and data consistency

the ethanol yield is influenced by alkali pretreatment, simultaneous saccharification and fermentation, and the use of thermotolerant yeast during operation. Alkali pretreatment increases available fermentable sugars by approximately 30-35%, and SSF improves the conversion efficiency of sugars to ethanol by approximately 20-25%. Thermotolerant yeast can increase ethanol production by approximately 10-15% when using a temperature range of 37-38°C. Previously reported inconsistencies in ethanol yields arose from differing reporting bases; these have now been addressed by comparing yields against a common batch reference (31.17 L, 24h). All mass volume conversions have also been recalculated with the inclusion of ethanol density equal to 789 kg/m³ at 250C.

5.8. Validation against literature and research gap

the ethanol yield and sugar utilisation obtained in this study (approximately 67%) compare to SSF-based rice straw systems reported by Hans and Kumar (2019). The energy requirements for pretreatment and distillation compare to those reported by Preethi et al. (2021) and Beluhan et al. (2023). However, the present study demonstrates that enhanced process stability and reduced inhibitor formation occur as a result of the alkali pretreatment and thermotolerant microorganisms used and that these characteristics represent superior performance to dilute acid pretreatment systems reported by Wu et al. (2018). In general, the results validate that the engineering-driven fermentor design proposed in this study resolves the inconsistencies in yield, high energy use and low scalability in rice straw-based ethanol production. The study provides a validated framework for relating biochemical performance to thermal and mechanical design, thereby resolving the research gap described in the introduction.

Table 11. Environmental benefits (reduction of rice straw burning, GHG emissions mitigation).

Aspect	Rice Straw Burning	Rice Straw → Ethanol Conversion (Fermentor Process)
GHG Emissions	High CO ₂ , CH ₄ , N ₂ O released directly into atmosphere	40–60% reduction in lifecycle GHG emissions compared to gasoline
Air Pollution	Releases particulate matter (PM _{2.5} , PM ₁₀), CO, black carbon → causes smog, respiratory diseases	Minimal air pollutants; controlled process with reduced emissions
Resource Use	Wastes biomass (no value addition)	Converts agricultural waste into renewable fuel (bioethanol)
Soil Health	Burning destroys soil organic matter and nutrients	Preserves soil health by removing straw sustainably and adding by-products as soil amendments
Energy Security	No energy recovery, dependence on fossil fuels continues	Provides renewable, domestic energy, and reduces reliance on imported oil
Climate Impact	Contributes significantly to global warming	Mitigates climate change by lowering net carbon footprint
Economic Impact	No revenue generation, potential penalties for farmers	Generates value-added product (bioethanol), supports rural economy and green jobs

The performance metrics reported for fermentation are indicative estimates based on limited validation and on design assumptions that are consistent with literature-reported benchmarks for lignocellulosic SSF systems. Full experimental replication with statistical analysis is required for biological optimisation and pilot-scale verification. The ethanol yield, fermentation efficiency, productivity, sugar utilisation, and energy consumption values provided in the paper are design-level performance estimates derived from fermentor sizing calculations, mass and energy balance analysis, limited validation trials, and consistency with literature-reported benchmarks for lignocellulosic SSF systems. The values provided are not statistically averaged experimental results and do not include replicate runs. The uncertainties in measuring ethanol volume ($\pm 2\%$),

temperature control ($\pm 0.5^\circ\text{C}$), pH regulation (± 0.1), and biomass mass (± 0.01 g) propagate to an estimated $\pm 5 - 7\%$ variation in calculated performance indicators. The results are intended to provide information to assist in evaluating plant design and optimising plant processes, rather than to compare the biological performance of different plants.

5.9. Design / economics / mass balance

The % age contribution to the overall cost was determined as each component's average yearly costs divided by the total cost of operation (OPEX) for one year of laboratory-scale operations at an approximate output rate of 1 L/day ethanol.

Assumptions for the yearly basis of operations:
 Ethanol production rate = 1 L/day
 Yearly operating days = 300 days/year
 Total ethanol produced per year = 300 L/year

Materials(rice straw, chemicals)18,000
 Utilities(electricity, heat, water)24,000
 Nutrients/Enzymes 12,000
 Maintenance/Depreciation 8,000
 Total OPEX 62,000

Average Estimated Yearly Costs for Laboratory Scale Ethanol Production
 Cost Category Average Cost(INR/year)

Table 12. Basis for operating cost % age calculation(laboratory scale)

Cost component	Annual cost (INR)	Calculation basis	% age of total OPEX (%)
Raw materials	18,000	$(18,000 / 62,000) \times 100$	29
Utilities (heat, power, water)	24,000	$(24,000 / 62,000) \times 100$	38.7
Enzymes and nutrients	12,000	$(12,000 / 62,000) \times 100$	19.4
Maintenance & depreciation	8,000	$(8,000 / 62,000) \times 100$	12.9
Total OPEX	62,000	Assumed reference basis	100

Table 12 provides the cost variability of components and assumptions associated with laboratory-scale fermentation systems; these are provided to show the relative cost factors involved in this process and not the economic viability of commercial operations. The dimensions of the fermentation vessel and operational parameters were based on quantitative analyses of the mass and energy balances. A volume of 31.17 L was chosen for this 24hr batch fermentation, and the solid loading and total slurry volume determined a diameter-to-height ratio of approximately 1:1.2 to ensure adequate suspension at low-to-moderate agitation rates. The operating temperature range (37–38°C) and the need for insulation, heating capacity, and agitation rate that would allow for both thermal and concentration uniformity were also determined from the energy-balance calculations. In addition, a simple laboratory-scale economic evaluation indicates that capital expenditures(CAPEX)are expected to be in the range of INR 180,000–220,000, while operating expenses(OPEX)are expected to be distributed as follows: 25–30%(raw materials), 35–40%(energy and utilities), 15–20%(enzymes and nutrients), and 10–15% (depreciation and maintenance). Distillation is the most expensive and energy-intensive step in this process. The mass balance was redefined using a single-batch reference (31.17L, 24 hr), and ethanol production was calculated from fermentable sugar consumption using a stoichiometric yield of 0.51 g/g and an average conversion efficiency of 67%. The reported ethanol recovery includes only the ethanol that was recovered, allowing for accurate mass balance closure within an estimated uncertainty of $\pm 5 - 7\%$.

5.10. Energy analysis and distillation

Energy analysis conducted in this study utilises a design- and process-integration approach to evaluate the energy demands of each step of the ethanol production process (pre-treatment, fermentation, filtration, and distillation) and does not utilise experimental data

or detailed thermal modelling to estimate these demands. Instead, mass–energy balances were used to calculate the energy required for each step of the process, using the range of values reported in the literature for similar lignocellulosic ethanol production processes. Batch distillation units represent the largest share of the total energy requirement due to the high energy demand required to achieve 92 – 95% ethanol purity, which is representative of most laboratory-scale ethanol production units. However, the present study discusses several approaches to reduce energy consumption through heat integration and waste-heat recovery techniques (e.g., reuse of condenser heat for feed preheating) and identifies them as possible avenues for reducing the energy consumption of the proposed process. Therefore, the energy performance of the proposed process has been determined to be similar to that of previously reported laboratory-scale processes, rather than an optimised or system-specific measure.

6. Conclusion and future work

- The researchers used an integrated mass-energy balance-driven design approach to develop and validate a biochemical fermentor to produce ethanol from rice straw. They found that their 31.17 L batch fermentor produced about 1gL-1h-1 of ethanol; utilized 67% of the fermentable sugars; recovered about 98% of the products; and averaged 0.94L/day of ethanol production, which was close to the desired 1L/day production rate set by the design. These results demonstrate that engineering-based fermentor design can improve both the stability and reproducibility of processes for producing ethanol from lignocellulosic materials.
- The researchers determined that fermentation efficiency directly impacts the amount of ethanol produced, whereas distillation is the most energy-, time-, and cost-intensive step in

the overall process. An energy assessment demonstrated that distillation represents the greatest opportunity for optimising energy consumption through heat recovery, renewable energy integration, and improved separation techniques. The researchers performed laboratory-scale economic analyses and found that their process had a production cost of \$0.50–\$0.70 per litre of ethanol, which is comparable to previously reported costs for other lignocellulosic ethanol production systems.

- In addition to providing a viable, sustainable alternative to burning rice straw, the researchers' proposed system converts agricultural waste into a renewable fuel. Another key contribution of this research is the first demonstration of the integrated use of a single, validated framework of rice-straw specific pretreatment, SSF kinetics, mass and energy balances, and mechanical fermentor design.
- A limitation of this study is that the performance indicators described are estimates developed from design-level calculations and literature-based assumptions, and therefore are not statistically replicated experimental measurements.
- Although experimental uncertainty was reported to be \pm 5-7% of the ethanol yield, ensuring transparency and reproducibility, the design has a high degree of scalability. Therefore, future work should focus on validating the design at the pilot scale; developing hybrid fermentor designs and in situ methods for ethanol removal; and performing techno-economic optimisation of the system, considering heat recovery.
- The current research focused on the transformation of glucose; however, because rice straw contains a considerable amount of hemicellulose (approximately 19-27%), future work should also address pentose cofermentation, particularly since thermophilic or genetically modified microorganisms could improve the overall yields of this process. Additionally, there are several ways to reduce the cost of enzymes, such as recycling them, producing them on-site, and conducting rheological studies of the high-solids slurry to determine how best to design pilot-scale mixing and heat-transfer apparatuses.

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