

ORIGINAL RESEARCH ARTICLE

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Sugar Palm Bioethanol: Fermentation Time, Turbo Yeast Dosage, and Rice-Husk-Heated Distillation for STEM Laboratory Education

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ABSTRACT

Background and Objective: Authentic STEM laboratory activities can connect renewable-energy science with measurement, engineering systems, quantitative reasoning, and sustainability. This study described sugar palm bioethanol production across fermentation-time and turbo-yeast conditions using rice-husk-heated fractional distillation and examined the workflow's prospective implications for STEM laboratory education. **Methods:** A 3 × 5 exploratory factorial arrangement combined 10, 20, and 30 g of turbo yeast per 11 L batch with fermentation periods of 24, 48, 72, 96, and 120 h. Each of 15 treatment combinations was processed once. Ethanol content, distillate volume, and post-fermentation pH were analyzed descriptively, and the workflow was prospectively mapped to science, technology, engineering, mathematics, and sustainability learning opportunities. **Results:** Ethanol content increased from 24 to 96 h at all three dosages and declined at 120 h. The highest observed value was 51% at 30 g and 96 h, with 545 mL of distillate and a qualitative pH reading of 3. The workflow supported conceptual links to fermentation science, measurement technology, biomass-heated separation, factorial data interpretation, and evidence-bounded reasoning. **Conclusion:** The study provides an exploratory process baseline and a defensible basis for developing a locally grounded STEM laboratory module. Because treatments were unreplicated and no students or learning outcomes were evaluated, neither statistical treatment effects nor instructional effectiveness can be claimed.

Keywords: Sugar palm sap; Bioethanol fermentation; Fractional distillation; Integrated STEM; Laboratory learning

INTRODUCTION

STEM laboratory education is strengthened when learners investigate authentic problems that require scientific explanation, technological measurement, engineering decision-making, and quantitative interpretation rather than merely following fixed procedures (Hofstein & Lunetta, 2004; Kelley & Knowles, 2016; National Research Council, 2012). Renewable-energy experiments can provide such contexts while also supporting sustainability-oriented education (UNESCO, 2020). In Indonesia, bioethanol is relevant to energy diversification because it can be produced from sugar-, starch-, or cellulose-containing biomass. Sugar palm sap (*Arenga pinnata*), which contains fermentable sugars, is especially suitable for small-scale investigation because it can be fermented without the hydrolysis step required for starch- or lignocellulose-based feedstocks (Amema et al., 2017; Manalu & Situmorang, 2023; Sangian et al., 2011).

Alcoholic fermentation is influenced by fermentation duration, substrate condition, acidity, nutrient availability, yeast physiology, and accumulated ethanol. Studies of *Saccharomyces cerevisiae* show that fermentation performance varies with strain robustness, nutrient environment, substrate concentration, and ethanol stress; therefore, extending fermentation time does not necessarily produce a proportional increase in ethanol content (Basso et al., 2008; Caspeta et al., 2019; Monteiro et al., 2018; Pereira et al.,

2011; Periadnadi et al., 2018). Turbo yeast is a commercial yeast-nutrient formulation intended for rapid, high-alcohol fermentation, but in this study its dosage is treated only as an operational factor because conventional yeast was not included as a comparator. After fermentation, fractional distillation can concentrate volatile components through repeated vaporization and condensation, although meaningful evaluation of separation performance requires feed and product composition together with documented operating conditions (Lara-Montano et al., 2019).

Rice husk adds a locally relevant resource-recovery dimension when used as the thermal input for distillation. Controlled rice-husk combustion is affected by airflow, temperature, fuel-bed condition, and combustion duration, so energy efficiency cannot be inferred without direct fuel and heat-transfer measurements (Piyathissa et al., 2023). Previous sugar-palm studies have examined fermentation duration, inoculum conditions, and distillation practices, while other work has addressed fractional distillation or rice-husk-derived bioenergy separately (Farhani et al., 2025; Maidangkay & Dosoputranto, 2021; Noviyanti et al., 2025; Permatasari et al., 2025; Riza et al., 2023; Salindeho, 2023; Simanjuntak et al., 2015). Within the evidence assembled for this study, the combined use of multiple turbo yeast dosages, a 24-120 h fermentation window, and rice-husk-heated fractional distillation for sugar palm sap remains comparatively underdocumented. The integrated configuration also has prospective educational value because one workflow can expose learners to fermentation, measurement, thermal separation, experimental design, data interpretation, and sustainability trade-offs.

Accordingly, this study aimed to (1) describe ethanol content, distillate volume, and post-fermentation pH across combinations of fermentation time and turbo yeast dosage; (2) document the distillate obtained using a rice-husk-heated fractional distillation system; and (3) map the experimental stages and evidential limitations prospectively onto STEM laboratory learning opportunities. The study addressed four questions: What ethanol-content pattern is observed across 24, 48, 72, 96, and 120 h at 10, 20, and 30 g of turbo yeast per 11 L batch? What distillate characteristics are obtained under the tested conditions? Which tested combination produces the highest observed ethanol content? How can the workflow be mapped to science, technology, engineering, mathematics, and sustainability learning? The working process expectation was that ethanol content would rise to an intermediate maximum and then decline; because each treatment combination was run once, this expectation was evaluated descriptively rather than statistically.

THEORETICAL OR CONCEPTUAL FRAMEWORK

The educational interpretation was guided by integrated STEM education, which emphasizes purposeful connections among science, technology, engineering, and mathematics around authentic problems and practices (Kelley & Knowles, 2016; National Research Council, 2012). Laboratory learning adds an inquiry-oriented emphasis on measurement, interpretation, and evidence-based explanation rather than procedural completion alone (Hofstein & Lunetta, 2004). Sustainability was treated as a cross-cutting context because the workflow uses sugar palm sap as a renewable biological resource and rice husk as an agricultural by-product, consistent with Education for Sustainable Development (UNESCO, 2020).

Operationally, the science dimension comprised fermentation, acidity, ethanol formation, vaporization, and condensation; technology comprised the alcoholmeter, pH indicator, thermometer, fractionating column, condenser, and related process equipment; engineering comprised system configuration, biomass heating, operating constraints, safety, and process improvement; and mathematics comprised the 3×5 treatment structure, tabulation, graphing, comparison, variability, and limits of inference. This framework was used only to map prospective learning opportunities. It was not used to claim educational effectiveness because no learners, instructional intervention, or learning outcomes were included.

METHOD

Research Design and Reporting Standard

This study used a quantitative two-factor exploratory laboratory experiment, complemented by a prospective STEM mapping of the workflow. Three turbo yeast dosages (10, 20, and 30 g) were crossed with five fermentation durations (24, 48, 72, 96, and 120 h), yielding 15 treatment combinations. Each combination was processed once; consequently, the design supports descriptive comparison but not estimation of within-cell experimental variance or inferential testing. The educational component was interpretive rather than intervention-based. No field-specific reporting checklist was documented for the original experiment; this report follows the structure and transparency requirements of the

EDUCATIONE Original Research Article template and explicitly distinguishes empirical observations from exploratory interpretation.

Context, Setting, and Study Period

Fermentation was conducted in Talawaan Village, North Minahasa, Indonesia, and distillation trials were conducted in a mechanical engineering laboratory at Politeknik Negeri Manado. Data collection took place from February to August 2026. The study used a small-scale renewable-energy process context in which locally sourced sugar palm sap was fermented and the resulting batches were processed through a rice-husk-heated fractional distillation apparatus.

Participants, Sampling, or Data Sources

The study involved no human participants. The primary data source comprised 15 experimental batches of sugar palm sap, one for each fermentation-time $\times$ yeast-dosage combination. Each batch contained 11 L of sap obtained from sugar palm trees in Talawaan Village. The design used the same raw-material source across treatment runs; no probabilistic sampling or sample-size calculation was applicable because the unit of analysis was the experimental batch rather than a human or institutional sample.

Variables, Constructs, and Operational Definitions

The manipulated process factors were fermentation time (24, 48, 72, 96, and 120 h) and turbo yeast dosage (10, 20, and 30 g per 11 L batch). The recorded outcomes were ethanol content (%) of the collected distillate, distillate volume (mL), and post-fermentation pH measured before distillation. The prospective educational mapping used four integrated STEM dimensions—science, technology, engineering, and mathematics—with sustainability treated as a cross-cutting context. Because pre-distillation ethanol concentration and residual sugar were unavailable, the terms ethanol yield, recovery, purification efficiency, and substrate conversion were not used as measured outcomes.

Instruments, Measures, and Data Collection

The process system consisted of a boiler or heating tank, fractionating column, condenser, cooling-water circulation system, and rice-husk-fueled burner. Measurements were made using a stopwatch, thermometer, alcoholmeter, graduated receiving container, and qualitative pH indicator paper. The alcoholmeter was checked against a stated 70% antiseptic alcohol reference before use. Because the reference was not identified as a certified ethanol standard and the alcoholmeter model, resolution, reading temperature, and temperature-correction procedure were not documented, this check is treated as an operational verification rather than full metrological calibration. Post-fermentation pH was recorded using indicator paper, so pH values should be interpreted as coarse qualitative readings.

Procedure or Intervention

Fresh sugar palm sap was filtered to remove debris. Turbo yeast (Angel Power) was added at 10, 20, or 30 g per 11 L batch, after which batches were fermented in sealed containers for 24, 48, 72, 96, or 120 h according to the treatment matrix. Post-fermentation pH was assessed before distillation. For each run, cooling-water circulation was activated, the fermented batch was loaded into the boiler, the rice-husk burner was ignited and allowed to stabilize, and the fuel bed was periodically tapped to remove ash and maintain combustion. Distillate collection began after vapor condensed at the outlet. The same apparatus and general operating sequence were used across all runs; however, exact operating temperature, rice-husk mass or feed rate, condenser-flow rate, and a standardized collection end point were not instrumented or reported. Figure 1 summarizes the experimental sequence and the measurement points used in the study.

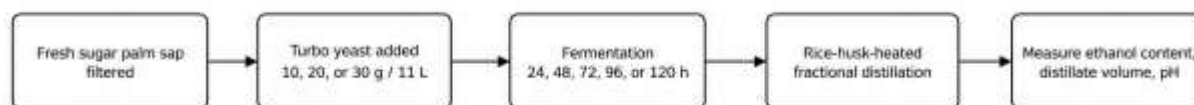


Figure 1. Experimental workflow for the 3 $\times$ 5 fermentation-distillation arrangement

Data Analysis

Ethanol content, distillate volume, and post-fermentation pH were tabulated for all 15 treatment combinations. Descriptive comparisons and line-graph visualization were used to identify patterns across fermentation time and yeast dosage and to identify the combination with the highest observed ethanol content. No analysis of variance or other inferential statistical test was performed because each treatment combination consisted of a single run. The available study record did not specify analysis software or version; therefore, none is reported. For the educational component, the experimental stages, instruments, data structure, process constraints, and evidential limitations were mapped prospectively to the four STEM dimensions defined in the conceptual framework.

Research Quality and Rigor

Procedural consistency was supported by use of the same raw-material source, batch volume, processing apparatus, and general operating sequence across runs. Interpretive rigor was supported by explicitly separating observed values from literature-supported mechanisms and by treating the STEM component as a prospective mapping rather than an effectiveness claim. Important constraints remain: qualitative pH measurement, a non-certified alcohol reference, unavailable baseline sugar and pre-distillation ethanol data, unreplicated treatment cells, and non-instrumented burner conditions. These limitations restrict precision, causal inference, and generalizability.

Ethical Considerations

The study did not involve human participants, human data, identifiable personal information, or animals. Therefore, human-subject informed consent and animal-research approval were not applicable. Standard laboratory safety procedures were followed for the rice-husk burner, heated surfaces, and distillation apparatus.

RESULTS

All 15 planned treatment combinations are represented in the analytical dataset. Because each row is a single experimental run rather than a replicated treatment mean, the results below are descriptive and do not include p values, confidence intervals, or effect sizes.

Ethanol Content Peaked at 96 h Across All Yeast Dosages

Ethanol content increased from 24 to 96 h at each of the three turbo yeast dosages and declined at 120 h. At 10 g, ethanol content rose from 20% at 24 h to 30% at 48 h, 40% at 72 h, and 42% at 96 h before decreasing to 41% at 120 h. At 20 g, the corresponding values were 28%, 34%, 43%, 47%, and 45%. At 30 g, the values were 36%, 39%, 46%, 51%, and 48%. The highest observed ethanol content was therefore 51% at 96 h with 30 g of turbo yeast.

Table 1. Ethanol Content, Distillate Volume, and Post-Fermentation pH by Fermentation Time and Turbo Yeast Dosage

Fermentation Time (h)	Yeast Dosage (g)	Ethanol Content (%)	Distillate Volume (mL)	Post-Fermentation pH
24	10	20	520	5
24	20	28	510	4-5
24	30	36	600	4
48	10	30	500	4-5
48	20	34	495	4
48	30	39	580	3-4
72	10	40	490	4
72	20	43	480	3-4
72	30	46	560	3-4
96	10	42	475	3-4
96	20	47	465	3-4
96	30	51	545	3

ORIGINAL RESEARCH ARTICLE

Fermentation Time (h)	Yeast Dosage (g)	Ethanol Content (%)	Distillate Volume (mL)	Post-Fermentation pH
120	10	41	460	4
120	20	45	450	3-4
120	30	48	530	3-4

Figure 2 displays the same ethanol-content pattern graphically. The lines are visual guides only and do not imply statistical significance.

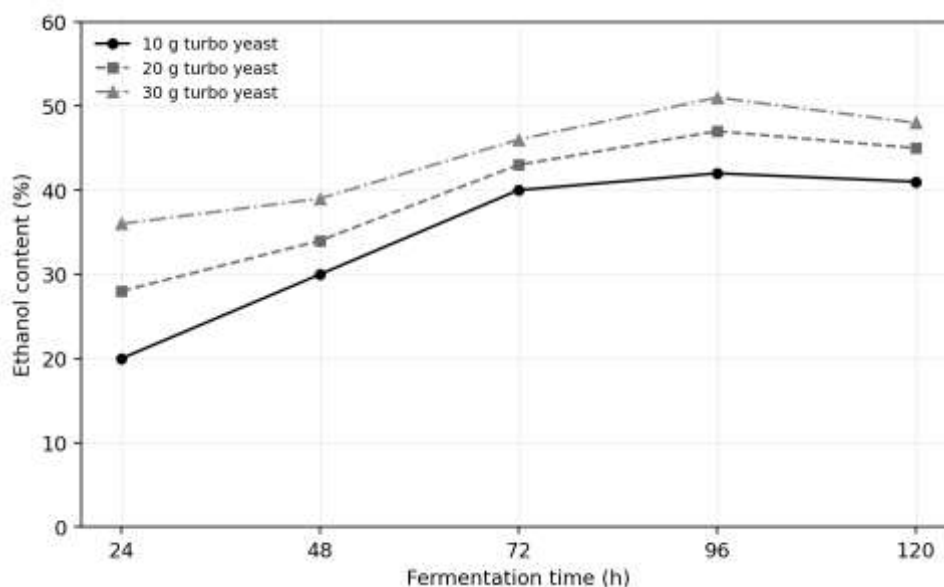


Figure 2. Ethanol content across fermentation time for the three turbo yeast dosages

Distillate Volume Declined with Longer Fermentation

Distillate volume decreased progressively with longer fermentation within each dosage series. For 10 g of turbo yeast, volume decreased from 520 mL at 24 h to 460 mL at 120 h; for 20 g, from 510 to 450 mL; and for 30 g, from 600 to 530 mL. The 30 g condition produced the largest collected volume at every fermentation duration. Post-fermentation pH generally shifted toward greater acidity, moving from approximately pH 4-5 in several earlier observations to approximately pH 3-4 in many 96-120 h observations. Because pH was measured with indicator paper and residual sugar, organic acids, microbial viability, dissolved oxygen, and mass balance were not measured, these values describe the observed process profile but do not identify a specific biochemical mechanism.

Prospective STEM Mapping of the Experimental Workflow

The prospective mapping identified learning opportunities in all four STEM dimensions. Science was represented by fermentation, acidity, ethanol formation, vaporization, and condensation; technology by measurement instruments and separation equipment; engineering by the biomass-heated distillation system, safety, operating constraints, and process standardization; and mathematics by the 3×5 treatment matrix, tabulation, graphing, comparison, variability, and limits of inference. Sustainability operated across these dimensions through the use of sugar palm sap and rice husk as locally relevant biological resources.

Table 2. Prospective Mapping of the Bioethanol Experiment to STEM Laboratory Learning

STEM Dimension	Experimental Basis	Prospective Laboratory Learning Focus
Science	Fermentation of sugar palm sap; pH change; ethanol formation; vaporization and condensation.	Hypothesis formulation; explanation of observed patterns; distinction between measured evidence and inferred mechanisms.
Technology	Alcoholmeter, thermometer, pH indicator, boiler, fractionating column, condenser, and cooling-water system.	Instrument selection; measurement limits; calibration awareness; safe equipment use; data-quality judgment.

ORIGINAL RESEARCH ARTICLE

STEM Dimension	Experimental Basis	Prospective Laboratory Learning Focus
Engineering	Rice-husk burner integrated with the distillation system; operating sequence and process constraints.	Systems thinking; design constraints; safety; process standardization; troubleshooting; improvement proposals.
Mathematics	3×5 treatment matrix; ethanol, volume, and pH data; graphical comparison across time and dosage.	Data organization; graph interpretation; comparison; optimization reasoning; replication; variability; limits of inference.

DISCUSSION

The principal process finding was a consistent descriptive increase in ethanol content from 24 to 96 h followed by a decline at 120 h across all three turbo yeast dosages, with the highest observed value of 51% occurring at 30 g and 96 h. Distillate volume declined as fermentation duration increased, while qualitative pH readings generally shifted toward greater acidity. These observations identify a potentially useful process condition for confirmation, but the single-run cells prevent statistical confirmation of time, dosage, or interaction effects. The study's educational contribution is distinct from the process result: the same workflow can be organized as a prospective integrated STEM laboratory context without claiming that it improves student learning.

Interpretation of Process Findings

The rise toward 96 h is compatible with established fermentation behavior in which substrate availability, nutrient status, yeast physiology, acidity, and increasing ethanol concentration jointly shape performance (Basso et al., 2008; Caspeta et al., 2019; Monteiro et al., 2018; Pereira et al., 2011). The decline after 96 h may be consistent with progressive substrate limitation, ethanol stress, acidification, or secondary metabolism, but these mechanisms were not measured directly and therefore remain literature-supported hypotheses rather than demonstrated causal explanations. The observed 51% value is higher than values reported in some earlier sugar-palm studies conducted under different fermentation and distillation conditions (Maidangkay & Dosoputranto, 2021; Riza et al., 2023), but cross-study differences do not demonstrate superiority of turbo yeast because yeast type was not experimentally compared here.

The rice-husk-heated fractional distillation apparatus produced collected distillate in all 15 runs, showing operational feasibility under the tested procedure. It does not establish purification improvement or thermal efficiency. Pre-distillation ethanol concentration, recovery ratio, reflux behavior, column efficiency, rice-husk consumption, airflow, and heat-transfer performance were not measured. This evidential boundary is important because distillation performance is normally interpreted relative to feed composition and operating variables, while rice-husk heat generation depends on combustion conditions such as airflow, fuel-bed characteristics, temperature, and duration (Lara-Montano et al., 2019; Piyathissa et al., 2023).

Theoretical and Methodological Contribution

The study's main process contribution is the integrated small-scale configuration rather than a new biological mechanism: fermentation time and turbo yeast dosage were varied within one sugar-palm system that used rice husk as the heat source for fractional distillation. Methodologically, the manuscript also demonstrates an evidence-bounded approach to an exploratory dataset by distinguishing observed values from causal or efficiency claims that the measurements cannot support. For STEM education, this limitation-aware stance is itself conceptually valuable because it makes replication, calibration, data quality, mass and energy balance, and inferential boundaries visible as part of scientific and engineering reasoning (Hofstein & Lunetta, 2004; Kelley & Knowles, 2016; National Research Council, 2012).

Implications for Education, Policy, and Practice

For instructors in STEM, vocational, and applied-engineering laboratory courses, the workflow can be developed into an inquiry-oriented module on renewable energy. Learners could formulate hypotheses about fermentation time and yeast dosage, operate and critique measurement tools, interpret the treatment matrix and line graph, and analyze how biomass combustion, heat transfer, condensation, safety, and process standardization affect what can be concluded from the system. The locally grounded use of sugar palm sap and rice husk can also support discussion of renewable resources, agricultural by-product recovery, and engineering trade-offs within Education for Sustainable Development (UNESCO, 2020).

The most defensible instructional emphasis is not an 'optimal recipe' but the evaluation of what the evidence does and does not justify.

These implications should be used as a design rationale rather than as evidence of educational effectiveness. No students participated and no achievement, engagement, competency, or instructional-effectiveness variables were measured. A subsequent education study should translate the workflow into a structured laboratory module with explicit learning outcomes, safety and measurement protocols, and direct assessment such as performance rubrics, laboratory reports, conceptual assessments, or pre-post measures of experimental-design and data-interpretation competence.

Limitations and Future Research

Several limitations constrain inference. Each treatment combination was processed once, so experimental variance and statistical significance could not be estimated. pH was measured with indicator paper rather than a calibrated digital meter. The alcoholmeter check used a stated 70% antiseptic alcohol reference, while instrument model, resolution, reading temperature, and temperature correction were not documented. Baseline sugar content and pre-distillation ethanol concentration were unavailable, preventing calculation of substrate conversion, ethanol recovery, or concentration change. Rice-husk mass or feed rate, airflow, heat-transfer rate, and thermal efficiency were not instrumented, and other fuel-quality parameters such as water and methanol content were not measured. Finally, the STEM component was conceptual only and did not involve classroom implementation or learning assessment.

Future process studies should replicate each treatment sufficiently for variance estimation and two-way analysis of fermentation-time and yeast-dosage factors; measure initial and residual sugar; use calibrated pH, temperature, and alcohol-concentration instrumentation with documented temperature correction; record pre- and post-distillation ethanol concentration; and characterize rice-husk fuel input, airflow, heat transfer, energy efficiency, and additional fuel-quality indicators. A direct comparison between turbo yeast and conventional yeast would be required before comparative superiority could be claimed. Future education research should implement the workflow as a defined STEM laboratory module and evaluate scientific inquiry, measurement competence, quantitative interpretation, engineering systems thinking, sustainability reasoning, feasibility, and safety using an appropriate educational research design.

CONCLUSION

Across the 15 single-run treatment combinations, ethanol content increased descriptively from 24 to 96 h and declined at 120 h for all three turbo yeast dosages. The highest observed ethanol content was 51% at 30 g of turbo yeast after 96 h, accompanied by 545 mL of distillate and a qualitative pH reading of 3. The rice-husk-heated fractional distillation system produced measurable distillate throughout the experiment, but the design does not support statistical treatment effects, quantified purification improvement, or thermal-efficiency claims. Its additional contribution is a prospective STEM laboratory framework that connects fermentation science, measurement technology, biomass-heated process engineering, factorial data interpretation, and sustainability. Because no learners or learning outcomes were examined, this educational contribution is a design basis for future testing rather than evidence of instructional effectiveness.

DECLARATIONS

Acknowledgments

Withheld for double-anonymous review. The complete acknowledgment statement will be restored in the non-anonymized version.

Author Contributions (CRediT)

Withheld for double-anonymous review. The complete CRediT contribution statement will be restored in the non-anonymized version.

Funding

This research received no external funding.

Ethics Approval

Not applicable. The study did not involve human participants, human data, identifiable personal information, or animals; it consisted of a materials-processing laboratory experiment.

Informed Consent and Assent

Not applicable because the study did not involve human participants.

Consent for Publication

Not applicable. The manuscript contains no identifiable participant information, images, or quotations.

Data, Code, and Materials Availability

The 15 treatment observations reported in Table 1 constitute the analytical dataset presented in this article. No analytic code was required for inferential analysis. Additional experimental records and procedural materials, if available, may be obtained from the corresponding author upon reasonable request after peer review.

Preregistration and Protocol

This study was not preregistered.

Conflict of Interest

The authors declare no conflict of interest.

Use of Generative AI and AI-Assisted Technologies

OpenAI ChatGPT (GPT-5.6 Sol) was used to assist with English-language editing, structural alignment with the EDUCATIONE template, and organization of the manuscript sections. It was not used to generate or analyze experimental data. The authors reviewed and verified the AI-assisted revisions and remain fully responsible for the accuracy, originality, confidentiality, and integrity of the manuscript.

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