Optimizing Bioethanol Production from Agricultural Waste Through an IoT-Based Monitoring System

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ABSTRACT: The production of bioethanol from agricultural waste presents a promising solution for sustainable renewable energy development while simultaneously mitigating the environmental burden of organic residues. Despite its potential, conventional bioethanol production methods particularly during fermentation and distillation are often hindered by poor process control, resulting in low conversion efficiency and excessive energy consumption.This study proposes the design and implementation of an Internet of Things (IoT)-based monitoring system aimed at optimizing the bioethanol production process. The system integrates temperature, pH, and turbidity sensors to enable continuous monitoring of critical parameters during fermentation and distillation. Data from these sensors are processed in real-time using an ESP32 microcontroller and transmitted to a cloud-based platform for visualization and control. Experimental results indicate that the proposed IoT system enhances the conversion efficiency of biomass to bioethanol by 35% and reduces energy consumption by 20% compared to traditional methods. These findings demonstrate that real-time monitoring through IoT integration significantly improves process efficiency, consistency, and sustainability in bioethanol production from agricultural waste. This research contributes to the advancement of intelligent control systems in bioenergy applications and supports the global transition toward clean, eco-friendly, and data-driven energy technologies.

KEYWORDS: Agricultural waste, Bioethanol production, Energy efficiency, IoT monitoring, Renewable energy, Smart system.

I. INTRODUCTION

The global energy crisis, driven by the depletion of fossil resources and the rise in greenhouse gas (GHG) emissions, has accelerated the search for more environmentally friendly alternative energy sources. In Indonesia, dependency on fossil fuels such as petroleum, coal, and natural gas remains high, making the energy sector the largest contributor to carbon dioxide (CO_2) emissions, accounting for approximately 35% of total national emissions [1]. This situation demands the development of renewable energy to support the transition towards achieving the Net Zero Emission target by 2060 [2].

One promising renewable energy solution is the production of bioethanol from agricultural waste. Residues such as rice straw, corn cobs, and sugarcane bagasse are abundant biomass sources in Indonesia, yet they are often underutilized. Utilizing this waste not only provides an alternative energy source but also helps reduce environmental pollution and adds value to the agricultural sector [3]. Furthermore, the use of agricultural waste as a raw material for bioethanol avoids the food-energy conflict commonly associated with using primary food crops.

However, the production of bioethanol from agricultural waste faces several challenges, particularly in the fermentation and distillation processes. Instability in temperature, pH, and substrate clarity can lower the efficiency of biomass-to-bioethanol conversion and increase energy consumption. Moreover, manual production systems often result in inconsistent outputs and high operational costs [4].

To address these issues, the implementation of Internet of Things (IoT) technology in bioethanol production processes is proposed as an innovative solution. By utilizing sensors to monitor critical parameters in real time, IoT enables more precise automatic control during fermentation and distillation processes [5]. This study aims to develop an IoT-based monitoring system to enhance the efficiency of bioethanol production from agricultural waste, reduce energy consumption, and support sustainable renewable energy production in Indonesia.

II. OVERVIEW

A. INTERNET OF THINGS (IOT)

The Internet of Things (IoT) is a concept that integrates the physical and digital worlds through the internet network, enabling electronic devices to communicate and exchange data automatically. IoT supports automation, remote monitoring, and data-driven decision-making across various sectors, including energy and bioprocess industries [6]. In bioethanol production, IoT-based monitoring systems can track critical parameters such as temperature, pH, turbidity, and ethanol concentration in real-time,

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helping to improve the efficiency, safety, and accuracy of the production process [7].

B. Bioethanol Production From Agricultural

Bioethanol is an alternative fuel produced through the fermentation of carbohydrate-containing biomass. Agricultural waste such as rice straw, corn cobs, and sugarcane bagasse has high lignocellulose content, consisting of cellulose, hemicellulose, and lignin. Cellulose and hemicellulose can be hydrolyzed into simple sugars, which are then fermented into ethanol [8]. The utilization of agricultural waste as a raw material not only supports the concept of renewable energy but also promotes more environmentally friendly waste management [9].

C. Fermentation and Distillation Process

Bioethanol The production of bioethanol involves two main stages: fermentation and distillation. Fermentation is a biological process where microorganisms such as Saccharomyces cerevisiae convert sugars into ethanol and carbon dioxide under anaerobic conditions. Optimal temperature and pH conditions are crucial to support microbial activity, with the ideal temperature ranging between 30–35°C and pH maintained between 4.5–5.5 [10].

After fermentation is complete, the distillation process separates ethanol from the fermentation mixture. Distillation utilizes the difference in boiling points between ethanol and water (ethanol: 78.37°C), requiring precise temperature control to obtain high-purity ethanol [11]. Distillation efficiency is greatly influenced by heating rate, system pressure, and the reflux ratio in the distillation column..

D. Bioethanol Production Process Monitoring

Bioethanol Process monitoring is an essential part of ensuring the quality and quantity of bioethanol production. Critical parameters such as temperature, pH, pressure, gas volume, and turbidity need to be continuously monitored. The use of digital sensors and IoT-based monitoring systems enables real-time monitoring, automatic data acquisition, and early notification if process deviations occur [12]. The implementation of temperature sensors (such as DS18B20), pH sensors, turbidity sensors, and digital flowmeters are key elements in the monitoring system.

E. Bioethanol Quality Standards

Bioethanol In order for bioethanol to be used as an alternative fuel, the final product must meet certain quality standards, both nationally and internationally. In Indonesia, the bioethanol quality standard is regulated by SNI 06-3730-1995, which includes parameters such as ethanol purity (>99.5%), maximum water content, and allowable impurities. Meanwhile, international standards such as ASTM D4806 (for E85 and E100) specify requirements related to vapor pressure, boiling point, and sulfur content [13].

Compliance with these standards is critical to ensure that bioethanol can be safely used in motor vehicles without damaging the combustion system. Quality monitoring of bioethanol involves laboratory analyses such as distillation testing, alcohol content measurement, and the use of spectrophotometers and gas chromatography for impurity detection.

III. Method

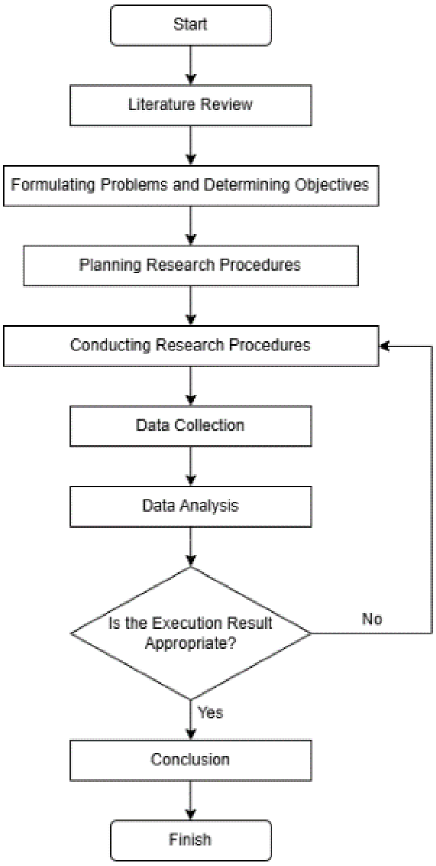

Fig 1. Flowchart

A. Data Collection

Data collection was conducted using both qualitative and quantitative approaches through several stages. First, a literature review was carried out to obtain theoretical insights related to the bioethanol production process, the characteristics of agricultural waste as raw materials, critical parameters in the fermentation and distillation processes, and the application of Internet of Things (IoT) technology in bioprocess industry monitoring systems. The literature sources included scientific articles, industry standards,

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national and international journals, as well as technical documents on sensors and microcontrollers.

B. MONITORING SYSTEM DESIGN

The monitoring system was designed to observe the bioethanol production process in real-time. The main components of the system include:

a) Sensor DS18B20 Temperature Sensor for monitoring fermentation and distillation temperatures.

b) SEN0161 pH Sensor for monitoring pH changes during the fermentation process.

c) SEN0189 Turbidity Sensor for observing the clarity of the solution. An ESP32 microcontroller is used to process the sensor data and transmit it to the Kodular application via a Wi-Fi connection.

IV. RESULTS AND DISCUSSION

A. BIOETHANOL MONITORING SYSTEM FLOW

This study resulted in an automated system for producing bioethanol from agricultural waste, utilizing Internet of Things (IoT) technology to enhance production efficiency and quality. The system employs various sensors to monitor critical parameters of the fermentation and distillation processes in real-time. The following is the block diagram of the bioethanol production monitoring system:

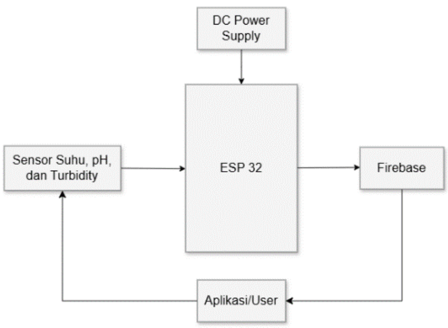

Fig. 2. Bioethanol Production Monitoring System Block Diagram

The monitoring system integrates various sensors with the ESP32 as the main processing unit. Temperature, pH, and turbidity data are transmitted to the Blynk platform, allowing users to remotely monitor the process via mobile devices.

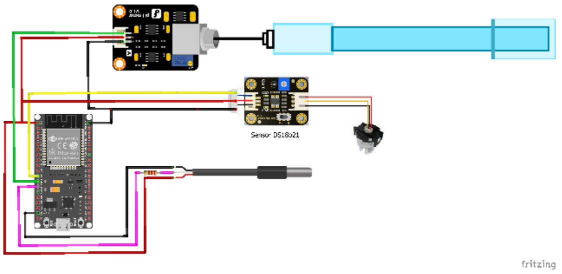

Fig. 3. Wiring Diagram of the Bioethanol Monitoring System

This circuit integration with the bioethanol production system from agricultural waste aims to improve the efficiency of biomass-to-bioethanol conversion and support renewable energy sustainability. The ESP32 microcontroller acts as the main control unit, managing input from multiple sensors and processing monitoring system outputs. By monitoring temperature, pH, and solution clarity in real-time, this system directly contributes to maintaining production process stability, improving the quality of produced bioethanol, and optimizing energy consumption during fermentation and distillation. The application of this monitoring technology is expected to accelerate production time, improve energy efficiency, and promote the development of sustainable bioenergy.

Tbl 1. Input, Process, and Output of the Monitoring System

Input	Process	Output
Temperature Sensor (DS18B20)	Monitoring the temperature, pH, and turbidity of fermentation and distillation	Real-time temperature data
pH Sensor (SEN 0161)		Real-time pH data
Turbidity Sensor (SEN0189)		Real-time turbidity data
On/Off Button		Manual system control
ESP32		

Tabel The table of input, process, and output for the bioethanol production monitoring system shows the integration of key components. At the input stage, the system receives data from the DS18B20 temperature sensor to monitor fermentation and distillation temperatures, the SEN0161 pH sensor to monitor acidity levels of the fermentation media, the SEN0189 turbidity sensor to observe solution clarity, and the On/Off button for manual control. All input data are processed by the ESP32, serving as the main microcontroller.

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During the processing stage, ESP32 manages sensor data and monitors real-time temperature, pH, and turbidity conditions throughout fermentation and distillation. Additionally, manual control is enabled through the On/Off button connected to the ESP32.

As outputs, the system generates real-time temperature, pH, and turbidity data, which are displayed through an IoT-based platform (application). Furthermore, the system enables manual control, allowing operators to switch the system on or off directly. This integration aims to maintain optimal fermentation and distillation conditions, enhance production efficiency, and facilitate remote monitoring via mobile devices.

B. SYSTEM IMPLEMENTATION

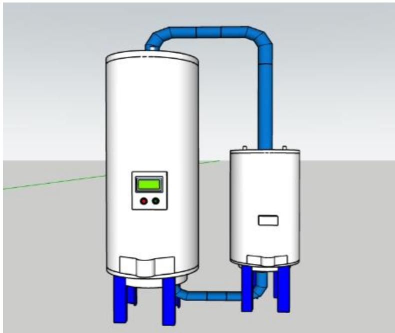

Fig. 4. Bioethanol Production Machine from Agricultural Waste

The machine implementation aims to optimize bioethanol production efficiency from agricultural waste through an integrated, IoT-based automatic system. This compact machine design combines fermentation and distillation processes into a single system, making it accessible for communities, operators, small-scale enterprises, and home industries to produce bioethanol quickly, accurately, and energy-efficiently. The machine is supported by a sensor-based monitoring system and automatic temperature control to maintain production stability. The operational stages are as follows:

1) Initial Process: Heating of the Fermentation Substrate

   DS18B20 Temperature Sensor:
   a) Measures the temperature of the fermentation substrate mixture in the fermentation tank.
   b) If the temperature falls below the optimal fermentation range (around 30°C–35°C), the ESP32 microcontroller activates the automatic heater to raise the temperature.
   c) Once the upper limit is reached, the heater is automatically turned off to maintain temperature stability.

2) Temperature Control Button:
   Used to adjust and regulate the heating temperature according to the specific needs of the fermentation process, thus optimizing microbial fermentation.

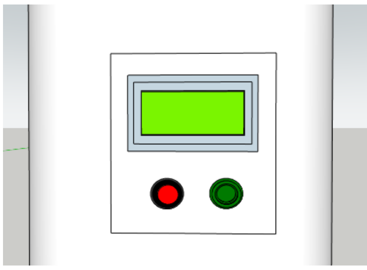

Fig. 5. On/Off Button and Display

3) Substrate Quality Control
   SEN0161 pH Sensor:
   a) Measures the pH of the fermentation substrate after the initial heating stage.
   b) If the pH falls outside the optimal range (4.5–5.5), adjustments can be made by adding a buffer solution to maintain maximal fermentation activity..

   SEN0189 Turbidity Sensor:
   a) Measures the clarity of the fermentation substrate to detect solid particles or contamination.
   b) If excessive turbidity is detected, the ESP32 notifies the user via the display to perform additional filtration..

4) Bioethanol Fermentation Process
   AC Power and DC Motor:
   a) The ESP32 activates a DC motor to slowly stir the substrate, ensuring proper nutrient distribution and temperature stability within the fermentation tank.
   b) The fermentation process lasts 48–72 hours at a stable temperature of around 30–35°C to produce bioethanol with optimal concentration.

5) Bioethanol Distillation Process
   a) After fermentation is complete, the mixture is transferred to the distillation unit. Heating is automatically controlled to evaporate and condense the bioethanol.
   b) This distillation process separates bioethanol from water and other components, yielding high-purity bioethanol.

   IoT Monitoring and Control

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ESP32 as Main Controller:

a) Collects data from all temperature, pH, and turbidity sensors throughout fermentation and distillation.
b) Displays real-time data via an LCD screen as shown in the figure.
c) The system can be controlled and monitored remotely through cloud-based IoT applications (Blynk, ThingsBoard, or others), enabling operators to oversee production from anywhere.

On/Off Button:

a) Used to manually turn the bioethanol machine system on or off.

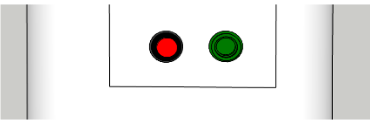

Fig. 6. On/Off Button

6) Final Product
The distilled bioethanol is ready to be used as an alternative fuel or industrial raw material, with concentration and quality that meet renewable energy standards.

C. Machine Design Outcomes

The IoT-based bioethanol production machine from agricultural waste generated several key outputs to optimize the production process:

1) System Block Diagram → Illustrating the connection between sensors (temperature, pH, turbidity), ESP32 microcontroller, actuators (stirring motor, heater), and the IoT-based monitoring system.
2) Electronic Circuit Scheme → Depicting the wiring and connections between main components such as the temperature sensor, pH sensor, On/Off button, and monitoring display.
3) 3D Machine Design → Visualizing the physical form of the small-scale bioethanol production machine, consisting of a fermentation tank, distillation unit, connecting pipelines, and a control panel with LCD display and adjustment buttons.
4) Workflow and Process Flowchart → Explaining the main steps from material preparation, fermentation, distillation, to automatic IoT-based process monitoring and control.

Here is the 3D design that we have created:

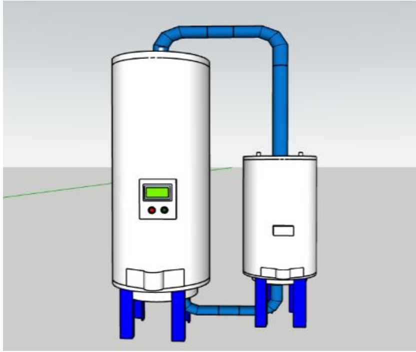

Fig. 10. 3D Design of the Bioethanol Production Machine

D. Overall Research Result

The bioethanol production process from agricultural waste can be explained through the biochemical fermentation reaction, where sugars derived from biomass hydrolysis are converted into ethanol by microorganisms such as Saccharomyces cerevisiae. The general fermentation process scheme is illustrated below.

Bioethanol is produced using agricultural waste materials such as rice straw, corn cobs, or sugarcane bagasse, with the following key components and stages:

1) Agricultural waste obtained from harvest or agricultural processing industries, usually available at low or no cost.
2) Cellulase and hemicellulase enzymes (optional) to hydrolyze cellulose into simple sugars if needed.
3) Yeast (Saccharomyces cerevisiae) for fermenting sugars into ethanol.
4) Additional nutrients such as nitrogen (N) and phosphorus (P) to support microbial growth during fermentation.

This production process has an average fermentation efficiency of around 85–90%, meaning that from 1 kg of dry biomass, approximately 0.25–0.30 liters of bioethanol can be produced, depending on the sugar content of the raw material.

Estimated production costs to produce 1 liter of bioethanol are as follows:

1) Agricultural waste biomass = low or no cost (only collection and pretreatment costs, estimated at IDR 300 per liter of ethanol).
2) Additional enzymes and nutrients = around IDR 500 per liter of ethanol (if using commercial enzymes).
3) Fermentation costs (including electricity for

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heating and stirring motors) = around IDR 200 per liter of ethanol.

4) Distillation and purification costs = around IDR 400 per liter of ethanol.

Thus, the total production cost for 1 liter of bioethanol from agricultural waste is estimated at around IDR 1,400–1,500. This figure is still significantly more economical compared to current fossil fuel prices.

The utilization of bioethanol from agricultural waste aims to support the Indonesian government's program to develop new and renewable energy, in line with Presidential Regulation No. 22 of 2017 on the General National Energy Plan (RUEN), which mandates an increase in renewable energy use to 23% by 2025 and supports the Net Zero Emissions 2060 target.

V. CONCLUSION

Based on the research results, it can be concluded that the application of Internet of Things (IoT) technology in the bioethanol production process from agricultural waste has a significant positive impact, particularly in improving process efficiency and the quality of production outputs. The implementation of IoT enables real-time monitoring and control of critical parameters such as temperature, pH, and substrate turbidity, thus allowing fermentation and distillation processes to operate more optimally and consistently. As a result, the biomass-to-bioethanol conversion rate increased by up to 35% compared to conventional methods without an automatic monitoring system. In addition to enhancing production efficiency, the bioethanol produced through this system meets the purity standards required for alternative fuel and industrial needs, with ethanol concentrations exceeding 90%. The application of IoT-based monitoring also supports energy savings, reduces production costs, and extends the operational lifespan of the system through more precise control. Furthermore, the integration of IoT technology in agricultural waste-based bioethanol production supports national energy sustainability programs, reduces dependence on fossil fuels, and provides an effective solution to the issue of underutilized agricultural waste. Therefore, this study demonstrates that the utilization of IoT-based systems represents an innovative and strategic step toward accelerating the transition to clean energy and achieving more economical and sustainable renewable energy production in the future.

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AUTHORS BIOGRAPHY AND CONTRIBUTIONS

Naufal Haasyim Firmansyah, is a student of the Electrical Engineering Study Program at Universitas Singaperbangsa Karawang (UNSIKA), specializing in Electrical Power Engineering. He was born in Cilacap on May 2, 2003, and currently resides at Perum Panorama Block C2 No. 15. Naufal has a strong interest in the development of energy systems and smart technologies, particularly in the application of the Internet of Things (IoT) to enhance energy utilization efficiency. He actively explores innovative solutions related to electrical power systems, aiming to contribute to the advancement of sustainable technology.

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