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Analysis Bio-oil of Pyrolysis Production Process from Corn Cobs

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Abstract. *Corn cobs are converted into bio-oil through pyrolysis using a simple pyrolysis apparatus at temperatures ranging from 300 to 400°C. This study evaluates the efficiency of the pyrolysis system, characterizes the compounds in corn cob bio-oil, and analyzes the economic viability of the method. The methods include the raw materials preparation (through drying and size reduction), development of bio-oil production equipment, implementation of pyrolysis and condensation processes, purification of the resulting bio-oil, compound analysis of the bio-oil, performance evaluation of the equipment, and engineering economic analysis. The successful production of high-quality bio-oil depends heavily on the precise and careful installation of all system components, including the pyrolysis reactor, smoke pipe, tar catcher, condenser, coil pipe, outlet pipe, liquid smoke container, water drum, and combustion furnace. The tool has a production capacity ranging from 0.89 to 0.96 kg per hour, with a coefficient of determination of 97.94%, and produced a yield of 32% to 34%. The bio-oil derived from corn cobs contained several compounds, including acetic acid, methyl ester, decenal, methyl 9,9-dideutero-octadecanal, phenol, 1-octanol, 2-butyl, 2-heptadecanone, myristaldehyde, octadecane, 1-chloro, and 1,9-tetradecadiene. The basic operating cost of the equipment is Rp 18,509.28 per kilogram, with a break-even point (BEP) of 238.43 kg per year. The basic production cost represents the minimum selling price required to achieve profitability. Biomass pyrolysis is a crucial thermal conversion technique with significant industrial and economic potential.*
Keywords: *corn cob; pyrolysis; analysis; yield.*

Type of the Paper: Regular Article.

1. Introduction

Corn cobs are byproducts generated during the shelling or threshing corn kernels, where the kernels are separated as the primary product, leaving the cobs as residual material. Corn is one of the major agricultural crops in Indonesia and Malaysia, producing large amounts of corn cob biomass that remain largely underutilized as value-added products [1]. Despite their considerable potential for diverse application, corn cobs are frequently underutilized and regarded as waste. Proper processing and utilization of corn byproducts can generate significant economic and environmental value. From each corn harvest, approximately 65% consists of corn kernels, while the remaining 35% comprises waste in the form of stalks, leaves, husks, and corn cobs [2]. Corn cob waste is abundant in Lima Puluh Kota Regency, West Sumatra Province, yet its utilization

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remains suboptimal. According to the BPS data of Limapuluh Kota Regency in 2022, corn production reached approximately 41,774 tons per year [3]. From this production volume, approximately 12,000 to 12,532 tons of corn cobs are generated annually. This substantial biomass resource presents significant potential for value-added utilization, particularly through pyrolysis processes.

Corn cobs consist of complex compounds, including lignin, hemicellulose, and cellulose, which possess significant potential for biological conversion into other valuable compounds [4]. Bio-oil derived from corn cobs, based on its pH, physical properties (such as specific gravity, color, and floating materials), as well as its phenol and acetic acid content, shows potential as an active agent that inhibits the growth of spoilage bacteria [5]. The primary component of corn cobs is lignocellulose, composed of cellulose, hemicellulose, and lignin. Their composition includes 6.04% ash, 15.70% lignin, 36.81% cellulose, 27.01% hemicellulose, and other components [6].

Corn cobs are processed into bio-oil through the pyrolysis process. In this process, the cobs are indirectly heated in a reactor, and resulting smoke passes through a condenser pipe, where it is transformed into liquid form known as liquid smoke or bio-oil. Pyrolysis, a thermochemical process conducted in the absence of oxygen, decomposes biomass into three main products: solid fuel (char), gas (syngas), and liquid (bio-oil) [7]. The yield of bio-oil increases with temperature climbs up to an optimal level but decreases when the temperature exceeds this point [8].

Corn cobs are abundantly available in Limapuluh Kota Regency but remain underutilized. To enhance their added value, a simple, low-cost, and easy-to-operate pyrolysis process has been introduced, making it accessible to small- and medium-sized enterprises. Corn cob pyrolysis was performed in a fixed-bed reactor at 350 °C, 400 °C, and 450 °C, using nitrogen to maintain an inert atmosphere. A cooling system collected condensable vapors, while a heating rate of 10 °C/min ensured uniform heat distribution throughout the 15 g corncob sample [9]. Pyrolysis at 500 °C and a heating rate of 10 °C/min produced a bio-oil yield of 33.32%, with chemical profiles dominated by aliphatic acids and phenolic compounds, confirming the suitability of these bio-oils, particularly from corn cob and vine rod—for biodiesel and value-added chemical applications [10]. In this study, pyrolysis was conducted at relatively low to medium temperatures (approximately 300–400 °C) to improve energy efficiency.

Specific calculations of bio-oil capacity and yield, along with the factors affecting them, have not been thoroughly investigated. Beyond technical considerations, it is also crucial to evaluate the small-scale economic feasibility and waste management impact, areas often overlooked in previous pyrolysis studies. Additionally, prior research has shown that the chemical composition of corncob pyrolysis bio-oil varies across studies. This study aims to quantify the primary compound, methyl ester, generated through this simple pyrolysis process. Gas chromatography-mass spectrometry (GC–MS) analysis showed that the bio-oil was mainly consisted of oxygenated compounds and hydrocarbons, including aliphatic hydrocarbons (28.768%), amines (10.472%), carboxylic acids (0.144%), phenols (0.047%), and esters (60.57%). These components significantly influenced the properties of the bio-oil [11].

The study examined the effects of temperature and heating rate on the yield and composition of pyrolysis products. Under microwave irradiation, a rapid pyrolysis rate and a bio-oil yield of up to 46.7 wt% were achieved, comparable to previous studies. GC–MS analysis revealed that temperature and heating rate significantly influenced both the bio-oil yield and phenolic compounds selectivity [12]. A comprehensive techno-economic evaluation is required to assess the viability and risks of large-scale implementation, which is critical for the commercialization of pyrolysis products [13]. Self-sustained pyrolysis can reduce bio-oil production costs, and its commercialization requires techno-economic analysis supported by predictive algorithms [14]. The corn cob pyrolysis process was conducted using a simple apparatus at temperatures ranging from 300 to 400°C. The study aims to evaluate the performance of the pyrolysis device, analyze the compounds in corn cob bio-oil, and assess the economics feasibility of the technique.

2. Materials and Methods

2.1. Time and Place of Research

This research was conducted from March to December 2023 at the Technical Implementation Unit of the Chemical Laboratory and Workshop, State Agricultural Polytechnic of Payakumbuh. The tools used included a bio-oil-producing pyrolysis tool (fixed-bed batch pyrolysis reactor), a high-temperature thermometer, a rotary evaporator, GC-MS, workshop equipment, laboratory analysis equipment, and others.

2.2. Raw Material Preparation

Corn cobs were obtained as agricultural waste from Harau Sub-district, Limapuluh Kota District, West Sumatra. The raw materials treatment involved: (a) Preparation: 10 kg of dried corn cobs with a moisture content of 8–10% were prepared, as lower moisture content accelerates the pyrolysis process [15]. (b) Size reduction: The dried samples were cut into 3 cm × 3 cm to facilitate combustion, as smaller sizes improve pyrolysis efficiency [16]. (c) Pyrolysis preparation: The dried, clean, and size-reduced samples were loaded into the pyrolysis reactor.

2.3. Development of Tools for Producing Bio-oil

The bio-oil-producing device was developed in prior research to generate bio-oil as a food preservative. In this competitive grant study, the apparatus was further refined into a methyl ester-producing device, the primary compound utilized in biodiesel production. Modifications were made to the pyrolysis reactor and combustion furnace to improve efficiency. The development plan emphasizes both structural and functional design enhancements Fig. 1.

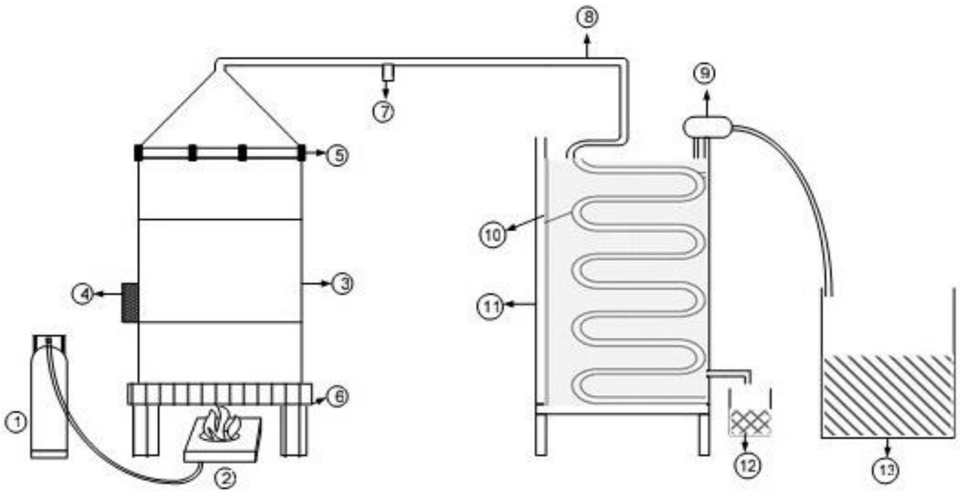


Image caption:
1. Gas Reactor
2. Combustion Furnace (Gas Stove)
3. Pyrolyzer
4. Thermocouple
5. Pyrolyzer cover locking bolt
6. Pyrolyzer position
7. Tar catcher
8. Smoke outlet pipe
9. Pump
10. Condenser spiral pipe
11. Condenser

Fig. 1. Design of a Pyrolysis Reactor

2.4 Pyrolysis Stage

The fire was ignited from the bottom to ensure complete combustion of the sample. The temperature and duration of bio-oil formation were monitored throughout the process. The resulting smoke flow was directed into the condensation reactor. Combustion in the pyrolysis reactor was repeated three times for each material.

2.5. Condensation Stage

The condensation (cooling) stage was conducted under flowing water conditions. Smoke from the pyrolysis reactor flows into the condenser, where water at normal temperature serves as the cooling medium. The smoke condenses, liquefied, and flows into a temporary storage column. The resulting condensate was then weighed and collected as a sample for further bio-oil analysis.

2.6. Bio-oil Purification Process

The process of purifying bio-oil involves obtaining pure bio-oil and separating it from tar: (a) the bio-oil obtained from condensation was left to settle for one week. The upper liquid layer was then collected and transferred to a distillation device; (b) unlike pyrolysis, distillation was conducted at approximately 150°C. The distillate was collected and filtered; (c) the distillate was filtered using activated zeolite, (d) this filtration process was intended to remove hazardous substances, such as tar, and obtain completely safe active substances.

2.7. Analysis of Bio-oil Compounds

A GC-MS instrument was used to identify the compounds present in bio-oil, employing an Rtx 5MS 30m column. The temperature program was set as follows: injector temperature at 280°C, initial column temperature of 50°C, a temperature increase of 10°C per minute up to 270°C, and interface temperature at 280°C. Prior to injection, the bio-oil was prepared by being stored or cooled, allowed to reach room temperature, homogenized by shaking, left to settle, and then injected into the GC-MS. The compounds were identified based on their retention times and mass spectra.

2.8. Analysis of Tool Performance

The performance of the bio-oil production tool is evaluated using equation (1) dan (2):

$$C\ (kg/h) = \frac{Bio - oil\ produced\ (kg)}{Pyrolysis\ time\ (hour)} \quad (1)$$

$$Y(\%) = \frac{Bio - oil\ produced\ (kg)\ \ x\ 100\%}{total\ amount\ of\ materials\ (kg)} \quad (2)$$

2.9. Engineering Economic Analysis

An engineering economic analysis was conducted to determine the manufacturing and operating costs of the tool. The calculations included fixed costs, variable costs, operating costs, and the break-even point (BEP).

3. Results and Discussion

3.1. Pyrolysis Equipment Assembly

This pyrolysis apparatus comprises distinct components that require precise assembly for operation. These components necessitate accurate and meticulous installation to ensure the production of the desired bio-oil. The pyrolysis reactor is constructed from 1.5 mm heat-resistant stainless steel plastic, capable of effectively channeling heat from the stove. It is designed as a closed system to prevent air entry, with combustion conducted indirectly. The reactor tube is equipped with a rust-resistant ½ inch stainless steel smoke pipe that directs combustion smoke to the cooling unit. The combustion smoke passes through a condenser pipe consisting of 12 spiral coils, through which cold water flows to accelerate condensation. The pyrolysis vapors cool in the condenser and condense into bio-oil. Heat for the pyrolysis reactor is supplied by a gas stove. The optimal working temperature is 250-300°C, with a heating rate of 20-30°C/min. Temperature measurements are taken using a digital thermometer. The pyrolysis tool circuit is shown in Fig. 2.

Fig. 2. Pyrolysis equipment assembly

3.2. Materials

Corn cobs are used as the primary material for producing liquid smoke due to their high cellulose, lignin, and hemicellulose. The moisture content of suitable materials for bio-oil pyrolysis should not exceed eight percent [17], as higher water content reduces phenols, acids, and formaldehyde in the smoke, while increasing carbonyl compounds, resulting in a more acidic product [18]. To achieve the desired moisture level, the corn cobs were sun-dried for four days, reducing their moisture content to 10%.

Corn cobs intended for pyrolysis are shredded to approximately 3x3 cm. Feedstock particle size significantly influences bio-oil yield [6]. Gani et al. [19] reported that corn cobs contain 12.44% moisture, 69.58% volatile matter, 15.40% fixed carbon, and 2.58% ash. Proximate analysis indicates a composition of 7.2% moisture, 78% volatile matter, 13% fixed carbon, and 1.8% ash [20]. Biomass with high volatile content is more suitable for producing bio-oil, while higher fixed carbon favors biochar generation [15]. Corn cobs are a promising energy resource due to their relatively high heating value (HHV) and lower ash content compared to other biomass types [21]. Corn cob waste is utilized in producing bio-oil, activated carbon, soil conditioners, and absorbent materials [22].

The high cellulose and hemicellulose content (76.23%) indicates that corn cobs have strong potential to yield substantial bio-oil through pyrolysis. The greatest mass loss, 61.92% occurred within the temperature range of 180–360°C [23]. Corn cobs contained 7.2% moisture, 72.9% volatile matter, 10.3% ash, and 9.6% fixed carbon, whereas the comparative sample had 0% moisture, 99.9% volatile matter, 0.08% ash, and 0.02% fixed carbon [24].

3.3. Bio-oil from Corn Cobs

Pyrolysis is the process of decomposition of raw materials, such as corn cobs, using combustion heat to produce bio-oil. Converting non-edible corn cob residues into green fuels and chemicals offers a valuable pathway to generate sustainable, low-carbon energy carriers that can replace fossil fuels [25]. During pyrolysis, temperatures of 300°C were reached, highlighting the critical role of temperature in determining the efficiency and yield of corn cob pyrolysis. As temperature increases, char yield decreases while volatile production rises. Larger particle sizes produce higher char yields and lower volatile yields. Additionally, higher heating rates enhance pyrolysis oil yield across all particle sizes, with the maximum yield reaching 25.40% for the corn cob fraction [26]. Pre-treatment via torrefaction before pyrolysis has been shown to improve certain physicochemical properties of bio-oil, increasing its suitability as a fuel [25].

However, the raw materials in the pyrolysis reactor fill only three-quarters of its volume, ensuring complete combustion through indirect heating. After 13 minutes of combustion, smoke flowed through the smoke pipe. The heavier fraction of smoke was captured by the tar trap, while the lighter fraction flowed to the condenser pipe, consisting of 12 water-cooled coils. The water in the condenser facilitates condensation of the smoke into liquid form. Initially, smoke was produced, and 5 minutes later, liquid smoke began to emerge. This process continues until the device stops producing bio-oil, typically after 3.5 hours. The effects of time and temperature on yield are shown in Fig. 3.

The operating temperature of this tool is 300 °C, corresponding to slow pyrolysis. At this temperature, the process yielded approximately 30–35% bio-oil and approximately 30% charcoal [27]. The influence of the temperature and reaction time on the tool's production capacity is illustrated in Fig. 3. As shown in the figure, bio-oil produced ranged from 0.89 to 0.96 kg per hour, from the pyrolysis of 10 kilograms of dried corn cobs.

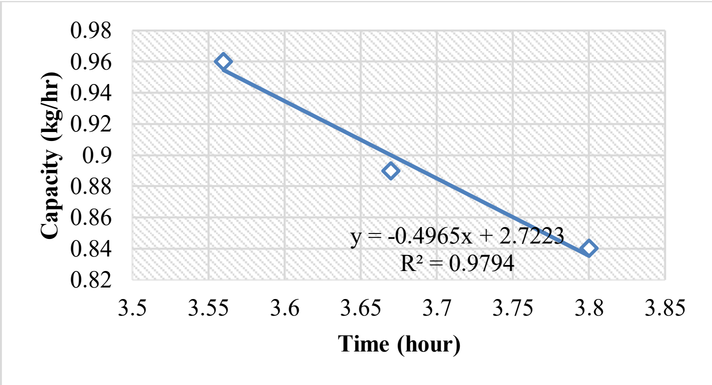


Fig. 3. Effect of processing time on bio-oil production capacity

The coefficient of determination (R^2) was 0.9794 (97.94 %), indicating that the model strongly explains the data. A higher R^2 generally reflects a better model fit. Here, 97.94% of the variation in yield is explained by the variables of temperature and time, while the remaining 2.06% is influenced by other factors, such as the moisture content of the material, fluctuating weather conditions, and other unmeasured variables. In addition, a smaller standard error indicates a more accurate model for data prediction [8]. The effect of time and temperature on yield is shown in Fig. 4.

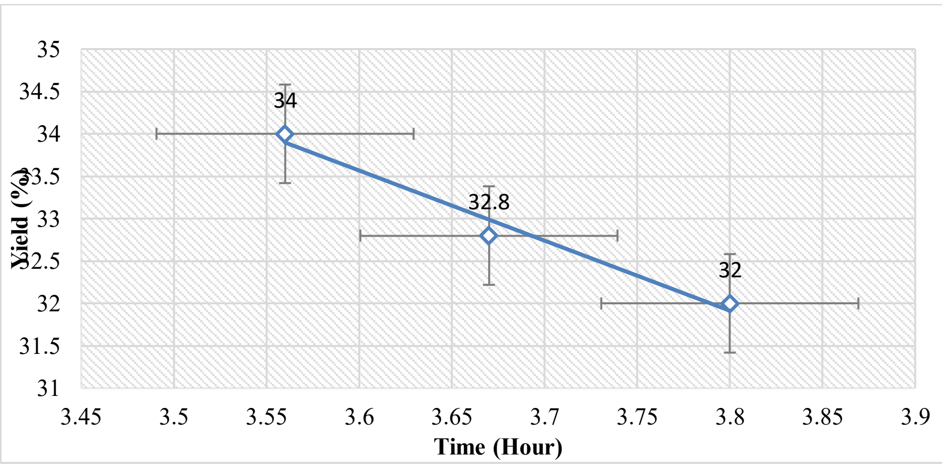


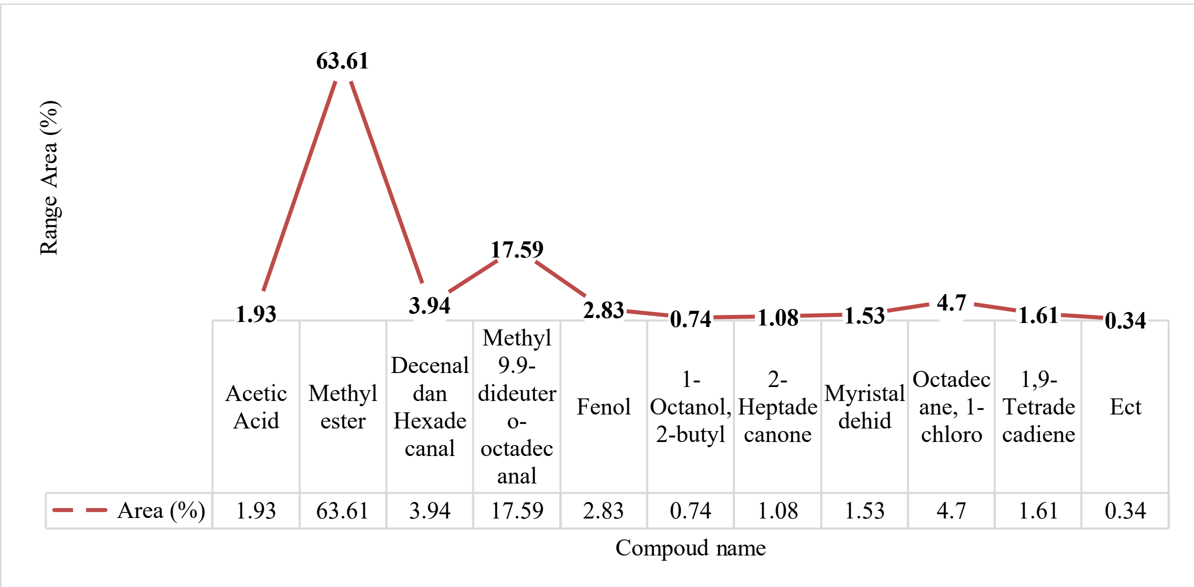
Fig. 4. Effect of processing time on bio-oil yield

The bio-oil generator exhibited an average capacity of 0.9 kg/hour and an average yield of 32.9%. The highest pyrolysis oil yield, 25.40%, was achieved from a specific corn cob fraction at a heating rate of 60 °C/min [26]. Although these results are promising, other studies have reported liquid smoke from coconut shells ranging from 40 to 45%.

Several factors contribute to the low yield of bio-oil yield: (a) the limited capacity of the pyrolysis reactor restricts production to a small scale, (b) the pyrolysis reactor's 3 mm thick plate shows heat transfer from the combustion furnace to the material, prolonging combustion times, and (c) the distance between the stove and the pyrolysis reactor affects the amount of heat reaching the material.

3.4. Determination and Analysis of Bio-oil Quality

High-quality bio-oil typically contains phenolic compounds, acetic acid, and carbonyl compounds. To assess its quality, GC/MS (Gas Chromatography–Mass Spectrometry) analysis was conducted to identify the chemical components present. This analysis was performed at the Chemistry Laboratory of the Payakumbuh State Agricultural Polytechnic. Corn cobs was found to contain acetic acid, methyl ester, decenal, methyl 9,9-dideutero-octadecanal, phenol, 1-octanol, 2-butyl, 2-heptadecanone, myristaldehyde, octadecane, 1-chloro, and 1,9-tetradecadiene. Bio-oil obtained from pyrolysis using an Fe-modified biochar catalyst primarily comprised simple phenolic compounds (52.02–59.40%), including phenol, 2-methoxyphenol, 4-ethylphenol, and p-cresol. These were followed by ketones (10.47–15.29%), aldehydes (6.83–11.44%), furans (2.40–4.15%), acids (0.53–2.86%), and trace nitrogen- and halogen-containing compounds [28]. The composition and number of these compounds are illustrated in Fig. 5.



	Acetic Acid	Methyl ester	Decenal dan Hexadecanal	Methyl 9.9-dideutero-octadecanal	Fenol	1-Octanol, 2-butyl	2-Heptadecanone	Myristaldehid	Octadecane, 1-chloro	1,9-Tetradecadiene	Ect
Area (%)	1.93	63.61	3.94	17.59	2.83	0.74	1.08	1.53	4.7	1.61	0.34

Fig. 5. Compounds contained in corn cob bio-oil

Methyl ester, present at 63.61%, is the predominant compound in corn cob bio-oil, formed through the reaction of fatty acids with methanol. In the energy sector, it is the primary constituent of biodiesel, commonly referred to as fatty acid methyl ester (FAME). This compound originates from acidic and carbonyl substances generated during the pyrolysis process and serves as a renewable alternative to conventional diesel fuel.

FAME is derived from vegetable oils rich in fatty acids—typically around 61–62%—and is commonly blended with petroleum-based diesel fuel [29]. Biodiesel produced via pyrolysis is considered an eco-friendly alternative to diesel fuel, generating lower emissions and minimal sulfur content [30]. Methyl ester yield from rice husk pyrolysis was relatively high, at 60.12% [31], while coconut shell-derived bio-oil contains 58% to 70% methyl ester [32]. Notably, the primary component of bio-oil from coconut shells through solar pyrolysis at 400 to 650 °C is phenol [8].

3.5. Engineering Economic Analysis

The equipment's operational cost was analyzed using engineering economic methods, including calculation of fixed costs, variable costs, prime costs, and break-even points. The assumptions underlying these cost calculations are presented in Table 1.

Table 1. Economic analysis

Parameters	Values
Assumption	
1) Equipment Purchase Price (P), Rp/unit	12000000
2) Final Equipment Cost (S), Rp/unit	1200000
3) Fuel Cost (Gas), Rp/kg	7000
4) Economic Lifespan (N), years	5
5) Capital Interest Rate (i), %	12
6) Daily Operating Hours, hours/day	8
7) Annual Operating Hours (X), hours/year	2016
8) Equipment Capacity (C), kg/hour	0.90
9) Product Yield, %	33
10) Selling Price of Liquid Smoke, Rp/kg	20000
11) Raw Material Purchase Price, Rp/kg	200
Fixed Cost	
1) Depreciation (D), Rp/year	900000
2) Rate of return on capital (I), Rp/year	330000
Total fixed costs, Rp/year	1230000
Variable Cost	
1) Fuel Cost, Rp/hour	3766.67
2) Operator Labor Cost, Rp/hour	10000
3) Repair and Maintenance Cost, Rp/hour	450
Total Variable cost, Rp/hour	16216.67
Basic Cost, Rp/kg	18509.28
Break Event Point (BEP) (kg/year)	238.43
Payback Period (year)	1.14

Based on Table 1, the basic operating cost of the equipment is Rp 18,509.28 per kilogram, with a break-even point (BEP) of 238.43 kg per year. The basic production cost is the minimum selling price required for profitability. The relatively low BEP indicates strong profit potential at higher production capacities. Labor and fuel costs are the dominant contributors to variable costs, implying that improving work efficiency and reducing fuel consumption can significantly enhance profitability. Overall, the equipment is economically efficient and can be profitable if annual production exceeds the BEP.

Optimizing operating hours and maximizing the equipment's production capacity is essential to achieve or surpass the BEP more rapidly. Economic analysis indicates that bio-oil production from corncobs yields a positive net value by the end of the project life. Among the evaluated options, it provides the fastest payback period due to the minimal fixed capital investment, despite lower long-term profitability [33]. Biomass pyrolysis is a crucial thermal conversion technique with significant industrial and economic prospects [34]. The Payback Period (PP) is the time required for an investment to recover its initial cost through net cash inflow; a PP of 1.14 years indicates that the initial investment is recouped in approximately one year and two months, after which additional returns constitute profit.

4. Conclusions

Corn cobs, often considered waste from the corn threshing process, holds significant potential for diverse application. However, this potential remains largely untapped. Proper and precise installation of these components is essential to ensure the efficient production of high-quality bio-oil. Optimal pyrolysis conditions were identified at 300 °C with a heating rate of 20–30 °C/min. Feedstock particle size significantly influenced bio-oil yield. The production equipment achieved an average capacity of 0.9 kg per hour and an average yield of 32.9%. Statistical analysis showed that 97.94% of yield variation was attributable to temperature and time, while the remaining 2.06% resulted from factors such as feedstock moisture content, fluctuating environmental conditions, and other unmeasured variables.

Methyl ester, comprising 63.61% of the total compounds identified in the bio-oil, was identified as the predominant constituent. This compound originates from acidic and carbonyl substances formed during the pyrolysis and serves as a primary component in biodiesel, offering renewable and sustainable alternatives to fossil diesel. An engineering economic analysis estimated the equipment's operating cost at Rp 18,509.28 per kilogram, with a BEP of 238.43 kg per year and PP 1.14 year. This basic production cost represents the minimum selling price required to achieve profitability. The pyrolysis system offers profitable potential for converting corncob waste into bio-oil, highlighting its promise for future commercialization.

Abbreviations

Not applicable.

Data availability statement

Data supporting this study will be made available on request.

CRediT authorship contribution statement

Sri Aulia Novita: Writing - Original Draft, Conceptualization, Methodology, Conceptual, Writing and Editing. **Perdana Putera**: Supervision, Validation, Writing Reviewing. **Musdar Effy Djinis**: Supervision, Visualization, Project administration. **Yuni Ernita**: Resources Methodology, Conceptual, Formal analysis, Writing and Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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