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PREPARATION AND BASIC CHARACTERIZATION OF LIQUID SMOKE FROM EMPTY OIL PALM FRUIT BUNCHES (EFB): INITIAL QUALITY ASSESSMENT BEFORE REFINING

Seno Aji[1]*, Yakin Berdikari Waruwu[2], Suratni Afrianti[3]
[1]Adiwangsa University, Jambi, Indonesia
[2]Agrotechnology Study Program, Faculty of Agriculture, Prima Indonesia University, Medan 20118, Indonesia
[3]Agro Sustainable Center, Prima Indonesia University, Medan 20117, Indonesia
**Corresponding author email:senostipap@gmail.com*

ABSTRACT

Empty oil palm fruit bunches (EFB) are a solid waste from the palm oil industry that are produced in large quantities and have the potential to be converted into liquid smoke through a pyrolysis process. This study aims to produce liquid smoke from EFB and characterize its basic properties—including pH, total acid, phenolic content, yield, and color—as a reference for initial quality before the purification stage. The pyrolysis process was carried out at a temperature of 400°C for ±3 hours without further purification. The results showed that the liquid smoke produced was pitch black, stable without sediment after 7 days of storage at room temperature, with a pH value of 3.10, total acid of 2.08%, phenolic content of 15.61 ppm, and a yield of 2.97%. The low pH value indicates a high content of organic acids resulting from the degradation of lignocellulose components, while the dark black color indicates that the product still contains tar compounds, thus categorizing it as grade 3 liquid smoke. Compared with previous studies on similar raw materials, the total acid value and phenolic content in this study were relatively lower, which is thought to be related to differences in process conditions and the absence of a purification stage. OPEFB liquid smoke products have the potential to be developed as natural preservatives and botanical pesticides, but require further purification stages in the form of precipitation, filtration, and distillation to improve the quality to a higher grade before being applied on an industrial scale. Further research with analytical repetition, characterization of compound composition (GC-MS), and optimization of the purification process is recommended to strengthen the validity and applicability of the results.

Keyword : Liquid smoke, Pyrolysis, Phenolic content

INTRODUCTION

Indonesia is one of the world's leading producers and exporters of palm oil. As palm oil production increases, the volume of waste generated from its processing also increases proportionally. One of the dominant solid wastes is empty oil palm bunches (EFB), the residue from pressing palm fruit that no longer contains oil. The volume of EFB waste produced is very large, accounting for approximately 22–23% of the total fresh fruit bunches processed (Anwar et al., 2015). This waste has a high crude fiber content and a significant water content, requiring proper handling and utilization to prevent environmental pollution and support the principles of a circular economy in the palm oil industry.

Chemically, OPEFB is composed of lignocellulosic components consisting of cellulose, hemicellulose, and lignin. These three components are the main components of plant biomass that have high potential to be converted into energy products and economically valuable chemicals through thermochemical processes such as pyrolysis (Fachry & Hartati, 2023). Mechanistically, these three polymers decompose at different temperature ranges: hemicellulose generally degrades in the range of 220–315°C, cellulose at 315–400°C, while lignin decomposes more slowly over a much wider temperature range, up to above 400°C (Demirbas, 2000; Stenseng et al., 2001). This difference in decomposition patterns also explains why the proportion of organic acids, carbonyl compounds, and phenolic compounds in liquid smoke is highly dependent on the temperature and duration of the pyrolysis process applied, because the hemicellulose fraction tends to contribute organic acids (especially acetic acid), while the lignin fraction contributes more phenolic compounds (Ball et al., 2004). The results of OPEFB pyrolysis itself produce three main fractions, namely non-condensable gases, solids (charcoal or biochar), and condensate liquid known as liquid smoke.

Liquid smoke is the result of the condensation of vapors from the combustion or pyrolysis of organic materials without the presence of oxygen (anaerobic pyrolysis). Sari (2018) showed that liquid smoke produced from the pyrolysis of OPEFB has a pH between 3.20 and 3.30 with a phenol content of 6.85% and acetic acid of 16.45%. These compounds are known to have high antimicrobial and antioxidant activity, making them potential natural preservatives and botanical pesticides. Research by Rachmawati et al. (2020) showed that a pyrolysis temperature of 400–450°C produces the highest yield and optimum acid and phenol content, while Fachry and Hartati (2023) reported the highest bio-oil yield of 33.2% at 450°C.

In addition to being a natural preservative, a number of studies report that liquid smoke has a broad spectrum antimicrobial function that is effective in suppressing the growth of bacteria and spoilage mold in food products (Lingbeck et al., 2014), so that it is widely developed as a natural alternative to synthetic preservatives in meat, fish and other processed food products (Snehanath et al., 2026). In the agricultural sector, the phenol and organic acid content in liquid smoke is also reported to be toxic to plant pests so that it has the potential to be used as a botanical pesticide, as shown in the application of liquid smoke from OPEFB to control leaf-destroying pests in mustard greens (Sari et al., 2018), liquid smoke from palm oil waste as a natural insecticide in wetlands (Soedijo et al., 2015, 2021), liquid smoke from cashew kernel shells as a pesticide (Tima et al., 2016), liquid smoke from coconut shells against armyworm mortality (Isa et al., 2019), liquid smoke as a biopesticide against major diseases of oil palm plants (Setiawan et al., 2024), and as a disinfectant based on rice husk pyrolysis products (Sukharnikov et al., 2015). The solid fraction resulting from OPEFB pyrolysis in the form of biochar also has its own added value as a soil amendment which has been proven to increase plant growth and yield in various land conditions, including peatlands and acidic soils (Rosenani et al., 2014a, 2014b; Mohd et al., 2017; Abdulrazzaq et al., 2014; Adu et al., 2022; Utami et al., 2024; Blankson et al., 2025, 2026), so that the utilization of OPEFB through pyrolysis has the potential to produce two valuable products simultaneously.

Although there has been extensive research on the production of liquid smoke from various biomass materials, studies specifically addressing the basic characterization of liquid smoke from OPEFB pyrolysis without purification are still relatively limited. Most previous studies have focused on the influence of pyrolysis temperature or feedstock type, without emphasizing the initial quality characteristics of the product before purification (Azhari et al., 2023). However, this initial quality characterization is crucial as a baseline for determining the need for and effectiveness of subsequent purification stages, as demonstrated by purification optimization using an advanced oxidation process with response surface methodology (Rasyid et al., 2025). Therefore, this study was conducted to produce liquid smoke from OPEFB through pyrolysis and examine its basic characteristics as a reference for further development into environmentally friendly agricultural and industrial raw materials.

RESEARCH METHODS

Location and Time of Research

This research was conducted at the Prima Indonesia University Laboratory in Medan, with liquid smoke quality parameters tested at an accredited third-party laboratory. The study lasted three months, from November 2025 to January 2026, and included raw material preparation, pyrolysis, laboratory analysis, and report preparation.

Materials and tools

The raw material used is empty oil palm bunches (EFB), which are cleaned of dirt and then dried in the sun for 2–3 days until the water content decreases. Afterward, the material is cut into small pieces to facilitate insertion into the pyrolysis reactor. The supporting material used is distilled water. The equipment includes a pyrolysis furnace, a water-cooled condenser, a storage container, a thermometer, an analytical balance, a measuring cylinder, and a funnel.

Pyrolysis Procedure

The prepared OPEFB is fed into a closed pyrolysis reactor, then the reactor is heated to a temperature of approximately 400°C and maintained for approximately 3 hours. The anaerobic conditions in the reactor cause the lignocellulosic material to decompose into three main fractions: non-condensable gas, solids (biochar), and condensable vapor. The resulting vapor is channeled to a water-cooled condenser to be condensed into liquid smoke. The liquid collected in the collection container is the raw liquid smoke resulting from pyrolysis and does not undergo further purification stages (sedimentation, filtration, or distillation) so it reflects the initial quality characteristics of the product. The process flow diagram is shown in Figure 1.

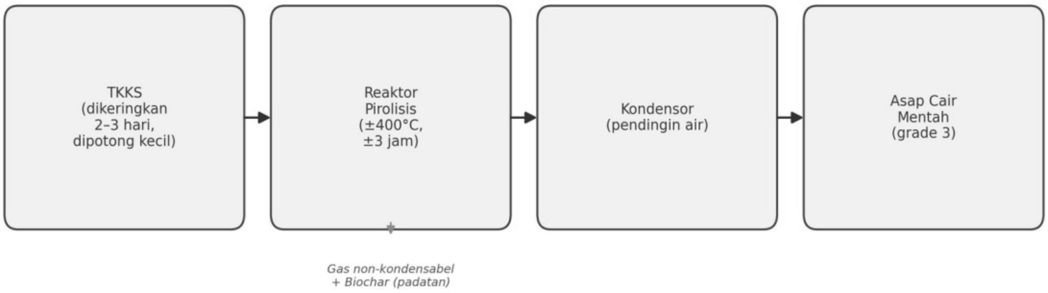

Figure 1. Flow diagram of the pyrolysis process of TKKS into liquid smoke

Quality Parameter Analysis

- pH — measured directly using a pH meter that has been calibrated with a standard buffer solution.
- Total acid — determined by titration using 0.1 N NaOH solution with phenolphthalein indicator until the titration end point is reached, expressed as percent acetic acid equivalents.
- Phenolic content — measured using a colorimetric reaction-based spectrophotometric method, with the absorbance of the sample solution compared against a standard curve.
- Yield — calculated as the ratio of the mass of liquid smoke produced to the mass of the initial TKKS raw material, expressed as a percentage.
- Color and physical stability — observed visually, including observing the presence or absence of sediment after storage for 7 days at room temperature.

Data analysis

The test data were analyzed quantitatively by comparing the obtained values with the published results of previous studies on similar raw materials and other lignocellulosic raw materials. Comparisons were presented in tabular and graphical form to facilitate interpretation of data trends. This research was exploratory in its initial stages; limitations related to the number of analytical replicates and their implications for the generalizability of the results are discussed further in section 3.7.RESULTS AND DISCUSSION

General Characteristics of Liquid Smoke

The results of the study showed that the liquid smoke produced from the pyrolysis process of OPEFB at a temperature of 400°C had physical characteristics in the form of a thick black color and showed no sediment after being left for 7 days at room temperature. Based on laboratory analysis, a pH value of 3.10, a total acid of 2.08%, a phenolic content of 15.61 ppm, and a yield of 2.97% were obtained.

A summary of the comparison of quality parameters with previous studies is presented in Table 1.

Table 1. Basic Characteristics of Liquid Smoke from Empty Oil Palm Fruit Bunches (EFB)

Parameter	The Results of This Research	Sari (2018) TKKS, Pyrolysis	Fauziati (2021) TKKS, Multistage Distillation
pH	3.10	3.20	± 3.50
Total Acid (%)	2.08	16.45 (acetic acid, GC)	not reported
Phenolic Content	15.61 ppm	6.85% (GC)	not reported
Yield (%)	2.97	not reported	not reported
Color	pitch black	Light brown (after distillation)	Clearer
Grade	**Grade 3**	**Grade 2**	**Grade 2 (indicative)**

Note: the total acid and phenolic values in Sari (2018) were measured through GC analysis, while this study used 0.1 N NaOH titration (total acid) and spectrophotometry (phenolic); the difference in analytical methods also affects the direct comparability of the figures.

Color and Physical Stability

The deep black color of liquid smoke indicates that the product still contains heavy compounds such as tar formed during the pyrolysis process. This is because no filtration or purification process was performed in this study, resulting in all pyrolysis fractions remaining mixed in a single liquid phase. This finding aligns with the findings of Karelius et al. (2020), which stated that liquid smoke without purification tends to be dark in color due to the high content of tar and other heavy compounds. In comparison, wood vinegar produced by fractional distillation generally has a light yellow to brown color because the heavy tar fraction has been separated through prolonged sedimentation and distillation (Fauziati, 2021).

The absence of sediment after 7 days of storage indicates that liquid smoke has relatively good short-term stability. This stability may be due to the presence of organic acids and phenolic compounds that have antimicrobial properties, thus inhibiting the activity of microorganisms that can cause changes or damage to the product (Sari et al., 2021). This finding is consistent with the broad-spectrum antimicrobial properties of liquid smoke that have been widely reported in various food matrices (Lingbeck et al., 2014; Snehanath et al., 2026), although long-term stability (more than 7 days) has not been tested in this study and needs to be confirmed through further observations.

pH Value and Total Acid

A pH of 3.10 indicates that the liquid smoke is acidic and contains organic acid compounds from the pyrolysis process. This value is still within the normal range for liquid smoke from OPEFB, as reported by Sari (2018) with a pH of 3.20, and is also in line with the pH range of liquid smoke from other lignocellulosic biomass in general, namely 2–4 (see Figure 2). Organic acids such as acetic acid and formic acid, which are formed from the decomposition of hemicellulose and cellulose, play a role in lowering the pH value. Fauziati (2021) stated that liquid smoke from fractional distillation of OPEFB has a pH of around 3.5 with a clearer color, indicating that purification can improve pH stability.

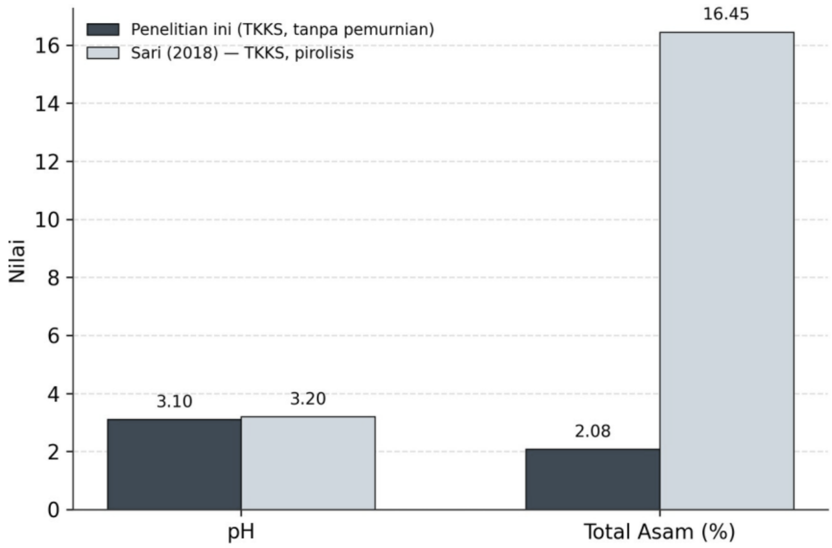

Figure 2. Comparison of pH and total acid of liquid smoke from TKKS in this study with Sari (2018)

The total acid content of 2.08% in this study is relatively lower than the results of Sari (2018) who reported an acetic acid content of 16.45% through GC analysis. This difference is likely influenced by differences in analytical methods (total acid titration versus GC-based quantification of specific compounds), as well as process conditions such as peak temperature, heating rate, and vapor residence time in the reactor. In general, the higher the tar and total dissolved solids content in liquid smoke, the higher the total acid value measured through titration (the liquid smoke industry generally titrates to an endpoint of pH 8.1–8.2 using NaOH), so the total acid value can also be an indirect indicator of the tar content of a liquid smoke product.

Phenolic Content

The phenolic content of 15.61 ppm reflects the presence of active compounds resulting from the degradation of lignocellulose components, particularly lignin. These compounds are the result of the degradation process of cellulose, hemicellulose, and lignin during the pyrolysis process; lignin primarily plays a role in the formation of phenolic compounds, while hemicellulose and cellulose produce more organic acid compounds (Ball et al., 2004). Faisal et al. (2020) stated that liquid smoke from OPEFB contains predominantly acetic acid and phenol. When compared to Sari's (2018) study with a phenol content of 6.85% and acetic acid of 16.45%, the total acid and phenolic values in this study were relatively lower, indicating that the active compound content is still not optimal due to the absence of a purification process and possible differences in measurement units (ppm on a total mass basis versus the percentage of components detected by GC).

This phenolic value is relevant in application because phenolic compounds in liquid smoke are known to provide antimicrobial and antioxidant activities that underlie its use as a natural food preservative (Lingbeck et al., 2014; Snehanath et al., 2026) and as a botanical pesticide, as shown in various pest control applications using liquid smoke from other biomass waste such as coconut shells (Isa et al., 2019), cashew nut shells (Tima et al., 2016), and palm oil solid waste itself (Sari et al., 2018; Soedijo et al., 2015, 2021; Setiawan et al., 2024).

Yield

The yield of liquid smoke obtained at 2.97% shows that the amount of product produced from the pyrolysis process in this study is still relatively low compared to the report by Fachry and Hartati (2023) who obtained the highest yield of 33.2% at a temperature of 450°C (Figure 3).

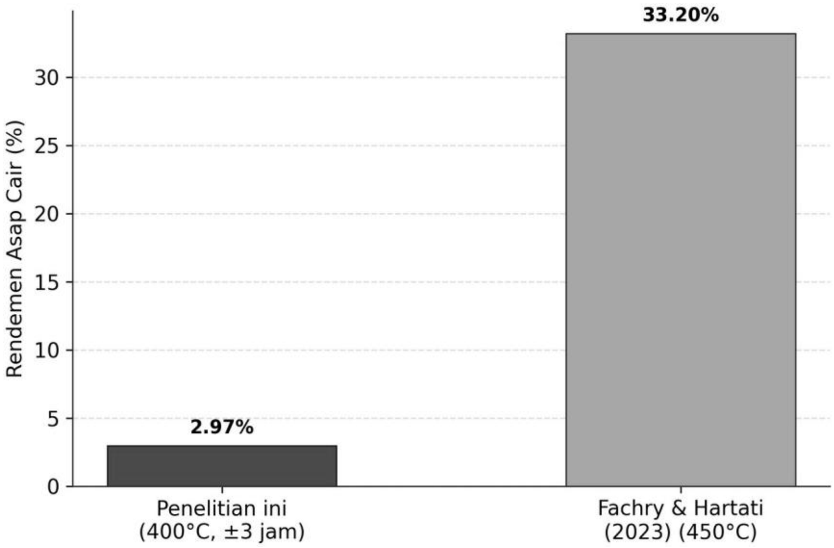

Figure 3. Comparison of liquid smoke yield of TKKS at different pyrolysis temperatures

This significant difference in yield can be influenced by various pyrolysis process conditions, such as peak temperature, heating rate, residence time, condensation system, and the moisture content characteristics of the raw materials used. Improving the condensation system through the use of a two-stage cooler can increase the efficiency of volatile vapor capture (Rachmawati et al., 2020). Furthermore, the particle size of the raw material and the initial drying rate also influence the rate of heat transfer into the material, thus impacting the efficiency of conversion into the liquid fraction compared to the gas and solid fractions (biochar).

Grade Classification and Practical Implications

Overall, the liquid smoke produced in this study can be categorized as grade 3 liquid smoke because it still contains high tar content, is dark in color, and has not undergone a refining process. The product quality characteristic profile is summarized in Figure 4.

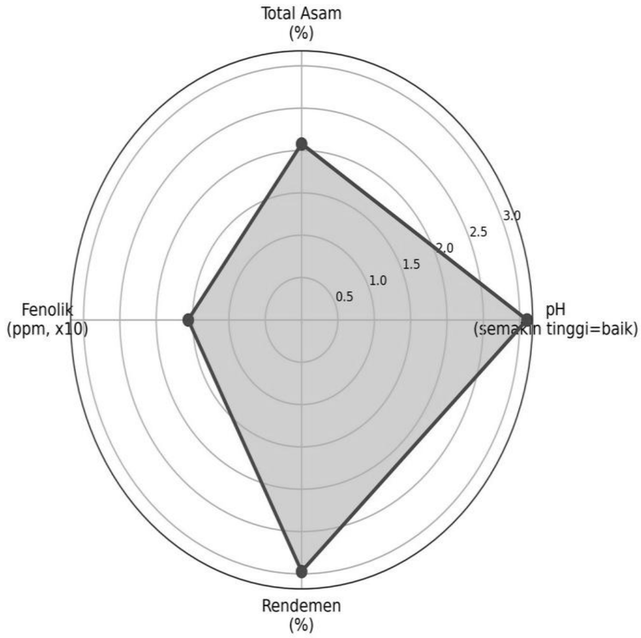

Figure 4. Quality characteristic profile of TKKS liquid smoke resulting from this study

Implementation of purification stages such as precipitation, distillation, and filtration is highly recommended to improve product quality to a higher level (grade 1 or 2) so that it can be used as a natural preservative, botanical pesticide, or industrial raw material (Lestari et al., 2015; Fauziati, 2021). Advanced purification approaches such as the advanced oxidation process optimized using response surface methodology have been proven to significantly improve the quality of OPEFB liquid smoke (Rasyid et al., 2025) and can serve as a reference for development in subsequent research stages.

Beyond utilizing the liquid fraction, it is important to emphasize that the pyrolysis process of OPEFB also produces a solid fraction in the form of biochar, which also has added value as a soil conditioner. Various studies have reported that the application of OPEFB biochar can improve soil physical-chemical properties, nutrient retention, and crop yields on peatlands and acidic soils (Rosenani et al., 2014a, 2014b; Abdulrazzaq et al., 2014; Mohd et al., 2017; Adu et al., 2022; Utami et al., 2024), including reducing greenhouse gas emissions when combined with compost (Blankson et al., 2025, 2026). Thus, the development of OPEFB pyrolysis has the potential to simultaneously produce two value-added products—liquid smoke and biochar—in line with the principle of integrated biomass waste utilization (zero-waste biorefinery).

Research Limitations

Several limitations need to be transparently stated. First, the quality characterization in this study was conducted at an early exploratory scale without multiple analytical replicates explicitly reported, so the variability and statistical significance between parameters cannot be ascertained. Second, compound identification was conducted at the aggregate parameter level (pH, total acid, total phenolic) without characterization of individual compound compositions by GC-MS, so direct comparisons with studies reporting specific compound compositions (e.g., Sari, 2018) should be read with caution due to differences in measurement basis. Third, the comparisons between studies in this discussion involve varying pyrolysis conditions (temperature, time, reactor type) and different forms of data reporting, making them descriptive-indicative in nature.

This is not a statistically controlled comparison. Further research with a factorial design (varying pyrolysis temperature and time), adequate analytical replicates, and GC-MS characterization of volatile compounds is recommended to strengthen the scientific validity of these findings before their adoption on an industrial scale.

CONCLUSION

Liquid smoke from empty oil palm fruit bunches (EFB) was successfully produced through a pyrolysis process at 400°C for approximately 3 hours. The basic characteristics of the resulting liquid smoke include a deep black color, a pH of 3.10, a total acidity of 2.08%, a phenolic content of 15.61 ppm, and a yield of 2.97%. The product is classified as grade 3 liquid smoke because it has not undergone a purification process and therefore still contains high levels of tar compounds.

The results of this study indicate that TKKS has the potential to be a valuable raw material for liquid smoke, with the potential for dual use as a natural preservative, botanical pesticide, and — through its solids fraction
— as biochar for soil amendment. However, the quality of the resulting liquid smoke still requires improvement through further purification processes such as filtration, distillation, and precipitation. The purification process is expected to reduce tar content, improve color clarity, and optimize the content of active compounds such as phenol and acetic acid so that the product can be optimally utilized in agricultural and industrial applications. Further research including analytical repetition, GC-MS characterization, and purification process optimization (e.g., through response surface methodology) is highly recommended to support the development of liquid smoke from OPEFB for industrial-scale applications.

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