International Journal of Emerging Research and Review
Homepage : https://ijoerar.net/index.php/ijoerar
p-ISSN : 3024-8825; e-ISSN : 3021-8950

IJOERAR, Vol. 4, No. 1, March 2026

The Potential of Teak Sawdust Waste as A Natural Antiseptic Can Be Explored Through an Extraction Process Using the Pyrolysis and Distillation Methods

Yudanti[1*], Rudiana Agustini[1], Zainul Arifin Imam Supardi[1]
[1*]Universitas Negeri Surabaya, Surabaya, Indonesia

DOI: https://doi.org/10.56707/ijoerar.v4i1.164

Sections Info

Article history:
Submitted: January 20, 2026
Final Revised: January 30, 2026
Accepted: January 31, 2026
Published: February 05, 2026

Keywords:
Antiseptic
Liquid Smoke
Distillation
Teak wood (Tectona grandis)
Pyrolysis

ABSTRACT

Objective: *This study investigates the influence of pyrolysis and distillation processes on the chemical composition and antibacterial potential of liquid smoke produced from teak (Tectona grandis) sawdust waste, aiming to identify bioactive compounds relevant for natural antiseptic applications.* ***Method:*** *Teak sawdust was subjected to oxygen-limited pyrolysis at temperatures of 250–400 °C to produce crude liquid smoke, which was subsequently purified through distillation. Both pyrolysis and distillation fractions were analyzed using Gas Chromatography–Mass Spectrometry (GC–MS) to characterize and compare their chemical compositions, focusing on organic acids, phenolic compounds, furans, carbonyls, and polycyclic aromatic hydrocarbons (PAHs).* ***Results:*** *GC–MS results demonstrated clear differences between the two processing methods. The pyrolysis fraction exhibited a higher proportion of organic acids (approximately 35%), contributing to lower pH and stronger antibacterial potential through synergistic effects of acids, aldehydes, furans, and phenolics. In contrast, the distillation process increased the relative phenolic content to around 40%, enriching stable compounds such as guaiacol, cresol, and syringol, while reducing highly volatile components. Both fractions contained low levels of PAHs, indicating that the processing conditions were adequately controlled and environmentally safe.* ***Novelty:*** *This study offers a comprehensive comparison of pyrolysis and distillation pathways in converting teak sawdust into liquid smoke, explicitly linking processing techniques to changes in chemical composition and antibacterial functionality. By integrating detailed GC–MS characterization with functional interpretation, this work advances current knowledge on biomass valorization and provides a scientific basis for tailoring liquid smoke as a natural and sustainable antiseptic.*

INTRODUCTION

The increasing incidence of bacterial contamination in food systems and the environment, particularly by pathogenic strains such as *Escherichia coli*, poses a serious challenge to public health and industrial safety (Ilsan et al., 2023; Hidayatullah et al., 2025). Although synthetic antiseptics remain widely used, their long-term application raises concerns related to toxicity, chemical residues, and the emergence of antimicrobial resistance (Puvača et al., 2021). These limitations have intensified interest in natural, biomass-derived antibacterial agents that are safer and more sustainable. In parallel, the furniture and wood-processing industries continue to generate large volumes of biomass waste, notably teak (*Tectona grandis*) sawdust, which is commonly disposed of through open burning or landfilling, thereby contributing to environmental pollution (Firdaus et al., 2022; Haryanto et al., 2021).

Teak sawdust is a lignocellulosic biomass rich in phenolic compounds, organic acids, and lignin-derived constituents with documented antibacterial potential (Asdaq et al., 2022; Vyas et al., 2019). Previous studies have explored various valorization pathways, including pyrolysis to produce wood vinegar or bio-oil (Gama et al., 2024; Rizal et al.,

2024) and conversion into antimicrobial activated carbon (de Paixão Cansado et al., 2022; Singh & Mishra, 2021). Other works have directly evaluated antibacterial activity of teak-derived fractions against foodborne and environmental pathogens (Jerzak et al., 2024; Sokamte et al., 2020). Collectively, these studies confirm that teak sawdust is a promising feedstock for natural antiseptic development.

However, despite extensive exploration of teak sawdust utilization, a critical knowledge gap remains regarding the explicit linkage between biomass processing pathways and the resulting chemical–functional properties. Most prior studies emphasize antibacterial testing outcomes without sufficient chemical characterization, making it difficult to identify which compound classes are responsible for the observed bioactivity. Conversely, studies that include chemical profiling often focus on a single processing method and do not systematically compare how different conversion routes alter the distribution of active compounds. As a result, the mechanistic relationship between processing technique, chemical composition, and antibacterial functionality remains poorly understood. This lack of comparative, process-oriented analysis limits both scientific interpretation and practical optimization of biomass-derived antiseptics.

Pyrolysis and distillation represent two fundamentally different yet complementary biomass processing approaches. Pyrolysis decomposes lignocellulosic structures under oxygen-limited conditions to generate a complex mixture of organic acids, phenolics, furans, aldehydes, and other reactive compounds. In contrast, distillation functions as a post-processing separation step that selectively enriches thermally stable and volatile components while removing heavier residues and unstable fractions. Although both processes are widely applied in biomass valorization, direct and systematic comparisons of pyrolysis-derived and distillation-refined liquid smoke from teak sawdust are still scarce, particularly in relation to how each process reshapes chemical composition relevant to antibacterial performance.

Therefore, this study addresses this gap by comparatively evaluating pyrolysis and distillation as sequential and contrasting processing routes for converting teak sawdust waste into liquid smoke with antiseptic potential. By integrating GC–MS-based chemical characterization with functional interpretation, this work clarifies how each process modifies the distribution of organic acids, phenolics, furans, carbonyls, and PAHs, and how these changes relate to antibacterial performance. This comparative process composition framework constitutes the main novelty of the study, advancing fundamental understanding of biomass conversion mechanisms while providing a scientific basis for selecting and tailoring processing strategies in sustainable antiseptic development and biomass waste valorization.

RESEARCH METHOD

This study employed a controlled two-stage laboratory experimental design to evaluate the effect of biomass processing methods on the chemical composition and antibacterial potential of liquid smoke derived from teak (*Tectona grandis*) sawdust waste. The independent variables were the processing method (pyrolysis and distillation) and the pyrolysis temperature range (250–400 °C). The dependent variables consisted of (i) chemical composition profiles of the resulting liquid smoke fractions, including organic acids, phenolics, furans, carbonyls, and polycyclic aromatic hydrocarbons (PAHs), and (ii) antibacterial indicators inferred from the distribution of bioactive compound groups and inhibition performance. This design enabled a direct comparison of how different processing pathways influence the formation and enrichment of antibacterial constituents.

The experiment was conducted at the Microbiology Laboratory and the Agricultural Products Quality Control Laboratory of SMK Negeri 3 Madiun, with chemical analysis performed at the Organic Chemistry Laboratory, Universitas Gadjah Mada, Yogyakarta. All experiments were conducted under identical biomass preparation conditions to ensure comparability between treatments.

The materials used included oven-dried teak sawdust waste, sterile distilled water, and standard laboratory reagents. The main equipment consisted of a laboratory-scale fixed-bed pyrolysis reactor, a condenser and liquid smoke collection system, a simple distillation unit equipped with temperature control, an analytical balance, and a Gas Chromatography–Mass Spectrometry (GC–MS) instrument, along with standard glassware such as beakers, funnels, and graduated cylinders.

Teak sawdust biomass was subjected to oxygen-limited pyrolysis at temperatures ranging from 250 to 400 °C using a laboratory-scale reactor. The heating rate was maintained at a controlled gradual increase (approximately 5–10 °C min^{-1}) to promote uniform thermal decomposition of lignocellulosic components. The residence time at the target temperature was maintained for 1–2 hours, allowing sufficient degradation of cellulose, hemicellulose, and lignin. Volatile vapors generated during pyrolysis were passed through a condenser and collected as crude liquid smoke. The collected liquid smoke was allowed to settle for 7–14 days at room temperature, enabling tar and heavy residues to separate by gravity. The clarified supernatant was then carefully decanted for further processing.

The clarified liquid smoke obtained from pyrolysis was further purified by atmospheric distillation. Distillation was conducted within a temperature range of approximately 100–200 °C, targeting the recovery of volatile and semi-volatile bioactive compounds while minimizing thermal degradation. Fractions were collected based on stable boiling temperature intervals, and the main distillate fraction was selected as the purified liquid smoke sample. Non-volatile residues and heavy tar fractions remaining in the distillation flask were discarded, ensuring consistency of the analyzed distillate.

Both pyrolysis-derived and distillation-refined liquid smoke samples were filtered, diluted, and transferred into GC–MS vials according to instrument protocols. GC–MS analysis was performed using standard operating conditions at the Organic Chemistry Laboratory, Universitas Gadjah Mada. Compound identification was based on retention time, mass spectral patterns, and comparison with the NIST mass spectral library (NIST, 2014). The relative abundance of each compound was determined from peak area percentages, which were subsequently grouped into major chemical classes to facilitate comparative interpretation between processing methods.

RESULTS AND DISCUSSION

Results

GC–MS analysis revealed distinct chemical profiles between the pyrolysis-derived and distillation-refined liquid smoke fractions. In the distillation fraction, a total of 57 chromatographic peaks were detected with a cumulative peak area of 57,516,028 units across retention times of 1.9–60 minutes. This wide retention-time distribution indicates the presence of both volatile and semi-volatile compounds, reflecting the selective separation effect of distillation rather than new compound formation (Liao et al., 2025).

The presence of numerous low-intensity peaks suggests that distillation yields a chemically cleaner but compositionally redistributed fraction (Fig. 1).

In comparison, the pyrolysis fraction exhibited 53 detected peaks within retention times of 2.0–57.6 minutes (Fig. 2). Although the number of detected compounds is slightly lower, the peak intensity distribution is more concentrated in early retention times, indicating a higher relative abundance of low-molecular-weight organic acids, aldehydes, and simple phenolics. This concentration pattern reflects direct lignocellulosic decomposition under oxygen-limited conditions, where cellulose and lignin thermally crack into reactive small molecules rather than being separated by boiling-point differences (Elhenawy et al., 2024).

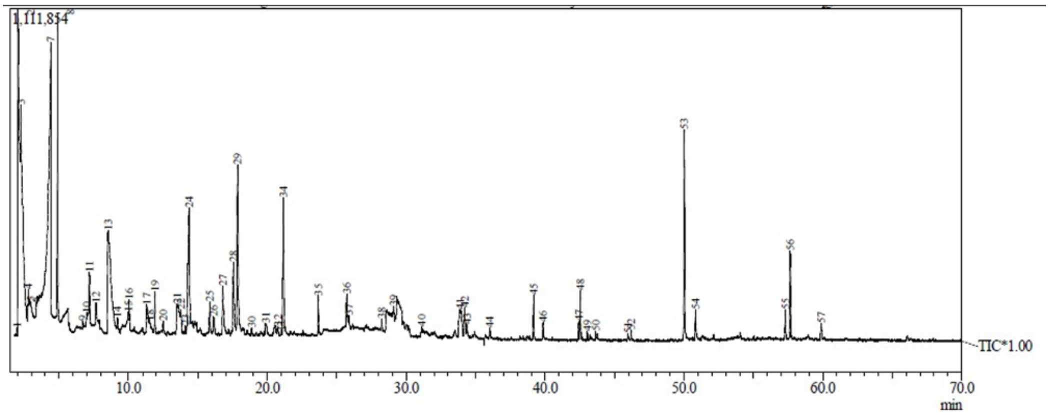

Figure 1. Shows the volatile and semi-volatile compound GC-MS profiles from distillation

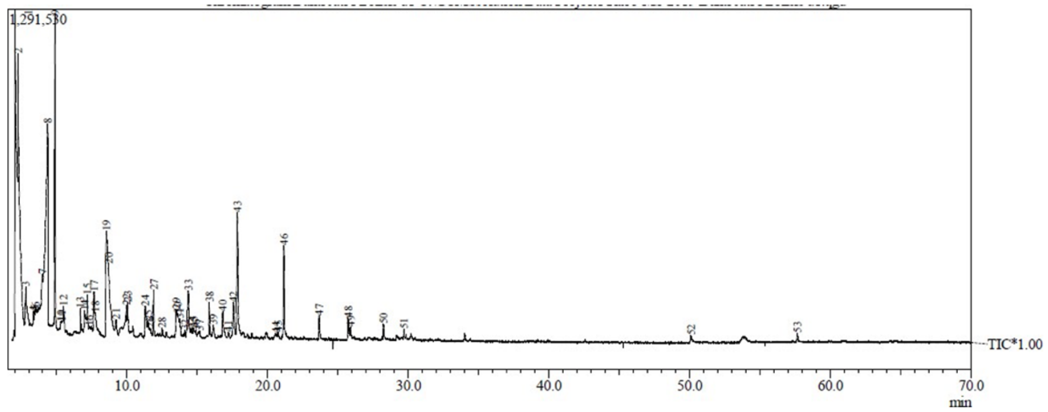

Figure 2. Shows the volatile and semi-volatile compound GC-MS profiles from pyrolysis of teak sawdust liquid smoke

Compared to its distillation fraction, the liquid smoke generated from pyrolysis has a more complicated chemical makeup, according to GC-MS analysis (Table 1). Numerous classes of chemicals, such as volatile esters, furan derivatives, light-to- medium aldehydes, and heavy aromatics, were found in the raw liquid smoke. This profile reflects the inherent characteristics of pyrolysis, where lignocellulose degrades at temperatures of 250–400 °C and produces a highly diverse mixture of volatile to semi-volatile products (Gani et al., 2024).

Following the distillation process of the pyrolysis liquid smoke, a number of chemical groups were eliminated. Small volatile esters, some longer-chain furan derivatives, some volatile aldehydes, and the majority of heavy aromatics and PAH are the main substances that are absent. Their absence is caused by the action of heat separation during distillation rather than a lack of compound synthesis (Sokamte et al., 2020).

Highly volatile compounds may be lost during reheating due to the lighter fraction produced by distillation, whereas heavier molecules typically stay in the residue (Mati et al., 2022). During the purification process, small esters readily break down or evaporate entirely. Some furan derivatives undergo ring-opening and change into tiny aldehydes because they are thermolabile (Haq et al., 2022). The GC-MS analysis does not show the peaks of heavy aromatic compounds because they are often kept in the tar/char phase and are not transferred into the distillate fraction.

Phenolic groups continued to be predominant in both analyses of the study's findings. Compared to esters and furans, phenols are more thermally stable and sufficiently volatile to be retained in the distillate. While some heavy lignin products are only present in the crude pyrolysis, phenol concentrations in the distillation and pyrolysis fractions do not differ significantly. The pattern of peak loss after distillation shows that the purification procedure removes highly volatile chemicals in addition to concentrating light fractions (Vidic et al., 2018). This explains why the distillation fraction's chemical composition looks simpler than the liquid smoke from crude pyrolysis.

Table 1. Compares the biochemical makeup of sawdust from teak wood using pyrolysis and distillation techniques.

No	R.Time (min)	Estimated Compound (Possibility)	Chemical Group	% Area Distillation	% Area Pyrolysis
1	1.950	Very light volatile (CO_2, solvent, air artifact)	Contaminants / Solvent	0.13	ND
2	2.050	Acetic acid / acetaldehyde / organic acids C2–C3; light aldehyde/ketone	Organic acid / aldehyde	13.25	16.16
3	2.252	Propionic acid / light furfural / C3–C4 volatile; light ketone	Organic acid / furan	13.08	16.68
4	2.795	Light alcohol/ketone (acetone, 2-butanone)	Ketone / alcohol	1.07	2.39
5	2.958	Organic acid / volatile ester	Ester / acid	0.47	ND
6	3.333	Light polar compound (aldehyde/ketone)	Aldehyde / ketone	0.13	0.20
–	3.424	Minor ketone alcohol	—	ND	0.22
–	3.966	Simple furan	Furan	ND	1.06
7	4.365–4.404	Phenol / guaiacol (2-methoxyphenol)	Aromatic phenol	15.61	13.33
8	4.889; 5.29–5.48	Phenol/methoxyphenol; HMF; furan derivative	Phenol / ketone / furan	3.55	4.41; 0.26–0.73
9	6.692	Furan/light aldehyde	Furan / aldehyde	0.20	0.51–0.73
10	6.975	Furfural / 5-methylfurfural	Furan aldehyde	0.63	ND
11	7.177–7.648	Light phenolic / cresol isomer / guaiacol minor	Phenol / cresol	1.11	1.35; 0.33; 1.68

No	R.Time (min)	Estimated Compound (Possibility)	Chemical Group	% Area Distillation	% Area Pyrolysis
12	7.663–7.750	Medium ketone/aldehyde	Ketone / aldehyde	0.53	0.61
13	8.527–8.696	Guaiacol / lignin derivative	Aromatic phenol	9.13	6.57; 4.23
14	9.198–9.207	Furan/medium ketone	Furan / ketone	0.26	0.80
15	9.955–9.965	Mid-volatility aldehyde/ketone	Carbonyl	0.30	0.80
16	10.041–10.049	Medium alcohol/ester	Ester / alcohol	0.44	0.69
17	11.295–11.302	Substituted phenolic (cresol/guaiacol deriv.)	Aromatic phenol	1.12	1.69
18	11.502–11.542	Light fatty acid / ester	Acid / ester	0.45	0.68
19	11.640–11.898	Heavy phenolate / aromatic ketone	Phenol / ketone	0.75	0.42; 1.22
20	12.492	Ester / polar aromatic	Ester / aromatic	0.24	0.28
21	13.515	Cresol (o/m/p) / guaiacol derivative	Cresol / phenol	2.31	1.25–1.07
22	13.767	Medium substituted phenolic	Phenol	0.62	0.66
23	14.105	Minor phenol	Phenol	0.13	0.21
24	14.359–15.1	4-methylguaiacol / methyl-phenol / syringol isomer	Aromatic phenol	5.45	2.53; 0.19–0.45
25	15.845–15.854	Medium ketone/aromatic	Ketone / aromatic	0.57	0.87
26	16.116–16.118	Aromatic ester/acid	Ester / acid	0.63	0.61
27	16.794–16.804	Phenol/lignin derivative	Phenol	1.40	0.91
28	17.207–17.567	Heavy phenolic / methoxy-phenol	Aromatic phenol	2.34	0.19; 1.36
29	17.850–17.858	2,6-Dimethoxyphenol (syringol)	Aromatic phenol	4.59	4.51
30	18.861	Furan/ketone	Furan / ketone	0.15	ND
31	19.879	Light aromatic acid / aldehyde	Acid / aromatic	0.41	ND
32	20.58–20.748	Ester / lipid fragment	Ester / lipid	0.17	0.26–0.28
33	20.983	Trace aromatic	Aromatic	0.09	ND
34	21.148–21.151	Phenolic acid (sinapic / vanillic)	Phenolic acid	2.70	2.63
35	23.660–23.663	Furan/medium ketone	Furan / ketone	0.81	0.58
36	25.710–25.720	Volatile fatty acid / ester	Fatty acid / ester	0.79	0.73
37	25.869–25.882	Minor aromatic	Small aromatic	0.29	0.40
38	28.226	Heavy aromatics (initial PAH)	PAH / aromatic	0.21	0.43
39	29.680–29.095	Heavy aromatic	Small PAH	0.21	0.21
40	31.116	Light Naphthalene-like PAH	PAH	0.21	ND
41	33.875	Naphthalene / phenanthrene	PAH	2.02	ND

No	R.Time (min)	Estimated Compound (Possibility)	Chemical Group	% Area Distillation	% Area Pyrolysis
42	34.213	PAH / heavy aromatic	PAH / aromatic	0.83	ND
43	34.371	Minor PAH	PAH	0.28	ND
44	36.014	Aromatic/polyaromatic	PAH	0.26	ND
45	39.168	Heavy aromatic / polyaromatic	PAH	0.62	ND
46	39.847	Heavy aromatic	PAH	0.34	ND
47	42.415	Heavy aromatic	PAH	0.28	ND
48	42.544	Heavy aromatic / terpenoid	Aromatic / terpenoid	0.81	ND
49	43.033	Minor PAH	PAH	0.14	ND
50	43.645	Minor PAH	PAH	0.13	ND
51	45.959	Heavy aromatic tertiary fragment	PAH	0.10	ND
52	46.201	Heavy aromatic	PAH	0.14	ND
53	50.023	Heavy aromatic / PAH condensation	PAH / heavy aromatic	4.02	ND
54	50.080-50.828	Heavy aromatic	PAH	0.78	0.20
55	57.304	Very heavy aromatic / residue	PAH / heavy	0.52	ND
56	57.649–57.652	Very heavy aromatic / polycyclic	PAH / heavy	1.77	0.24
57	59.883	Residual heavy aromatics	PAH / heavy	0.42	ND

The organic acid content was 35% during the pyrolysis step, compared to 26% in the distillation fraction. On the other hand, following distillation, the total phenol level rose to 40%, surpassing the 35% found during the pyrolysis process. Distillation yielded 10% for the furan and carbonyl chemical groups, which is marginally more than the pyrolysis fraction of 8% (Fig. 3).

Previous studies reveal that teak wood sawdust has a complicated chemical profile full of volatile chemicals. More than 80 components are produced by pyrolyzing teak wood, including levoglucosan (±26%), acetic acid (6–10%), and phenolics such isoeugenol (3–4%) and 4-ethenyl-2-methoxyphenol (±7%) (de Castro et al., 2022). 2-methylanthraquinone and other common teak extractives are present as significant chemical indicators (Charoensit et al., 2021). A bio-crude fraction rich in carbonyls, phenolics, and furan derivatives is produced by hydrothermally processing teak biomass (Asdaq et al., 2022).

In general, organic acids have higher boiling temperatures, are less volatile, and are more polar (Charoensit et al., 2021). There is less organic acid in the distillate fraction when the crude liquid smoke is reheated during the distillation process because some of the organic acids do not evaporate and stay in the residue (Gani et al., 2024).

On the other hand, compared to organic acids, phenolic compounds like guaiacol, syringol, and cresol tend to be more thermally stable and have low volatility. Phenolic chemicals are more readily carried over with the vapor during distillation, which raises their concentration to 40%. Additionally, phenols maintain their dominance in the distillation fraction due to their aromatic structure, which is resistant to mild degradation (Budianto et al., 2025).

According to the study's findings, furan and carbonyl molecules behave differently. Because they come from the breakdown of cellulose and hemicellulose, which produces light molecules like furfural, 5-HMF, and acetaldehyde, this category is typically more volatile. Due to their high volatility, these compounds become more concentrated in the vapor phase during distillation, resulting in a distillation fraction of 10%, which is marginally greater than the original value of 8%.

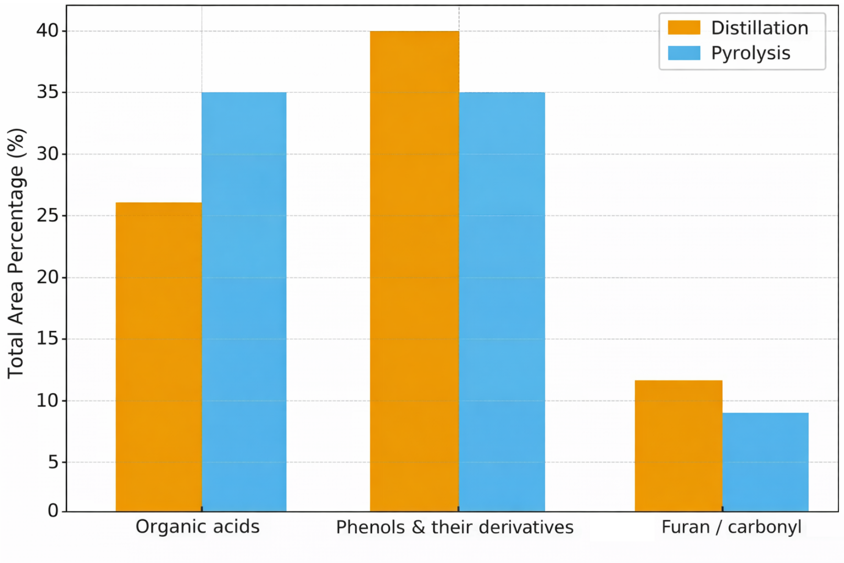

Figure 2. Bioactive chemical groups from the pyrolysis and distillation procedures of teak sawdust liquid smoke are compared.

Discussion

The total phenol content of the distillation fraction was approximately 40% greater than that of the pyrolysis fraction, which was approximately 35%. The pyrolysis liquid smoke produced a broader inhibition zone, according to the inhibition test results (Fig. 3). Although distillation produces a fraction with purer phenols, the majority of reactive volatile chemicals are lost due to fractional heating (Elkasabi et al., 2023). These substances, which include furfural, light ketones, tiny aldehydes (C2–C4), and high-energy organic acids, greatly enhance antibacterial action. The concentration of these compounds in the distillation fraction decreases because they are extremely volatile and unstable throughout the purification stage (Peh et al., 2020).

On the other hand, more aggressive, bactericidal chemicals are retained in liquid smoke from pyrolysis. Because pyrolysis has a lower pH (1.8–2.5) and a larger organic acid content (about 35%), bacteria are subjected to greater environmental stress through an acidification mechanism. Additionally, because pyrolysis does not go through refractionation, it leaves behind a more complex and reactive mixture of aldehyde-phenol-furan molecules. The combination of strong acidic effects, reactive aldehydes, and moderate phenols creates a synergy that enhances the ability to damage bacterial cell membranes. The bio-oil fraction resulting from durian peel pyrolysis, which is high in phenols, demonstrated strong antibacterial activity against *Staphylococcus aureus* and *E. coli* (Mashuni et al., 2024). Compared to the crude pyrolysis fraction, fractional distillation raises the quality of phenols by around 40% (Pramono et al., 2022). Although they can be lost during purification, volatile substances like ketones and light aldehydes also contribute to antibacterial action (El Farissi et al., 2022). Despite having a reduced overall phenol content, pyrolysis liquid smoke can display a broader inhibitory zone due to the combination of these phenols and volatile chemicals (Guo et al., 2018). These useful findings show that liquid smoke has a lot of promise as a natural preservative and an eco-friendly antibacterial agent, which is relevant to everyday life.

Recycling and sustainable waste management are further supported by the use of sawdust waste from teak wood for the creation of liquid smoke. As a result, this hands-on practice fosters environmental awareness in addition to improving comprehension of scientific ideas. Students learned how to observe, document data, evaluate outcomes, and make inferences based on experimental evidence throughout the practicum. Students can see physical changes at various phases of the process as part of the integration of physics topics. When a solid material is heated to produce smoke (the gas phase), it undergoes a change of state when it cools and condenses into a liquid. At this point, temperature variation causes a change in physical form rather than the formation of a new substance. The creation of new substances is a sign of the integration of chemical change principles.

The pyrolysis process causes complex compounds in teak wood, such as cellulose, hemicellulose, and lignin, to decompose into simpler chemical compounds. The formation of compounds such as acetic acid, phenols, and carbonyls provides evidence of chemical reactions. Changes in color, the distinctive smoky odor, and the acidic properties of the liquid smoke serve as indicators of chemical changes that can be observed by students. Because liquid smoke contains phenol and acid chemicals that function as natural preservatives and antibacterial agents, there is a relationship between chemical ideas and their everyday uses. Students can also see how chemical compounds alter food items' shelf life or prevent microbes from growing through basic food testing. As a result, students comprehend that chemical substances have practical uses for human benefit and are not merely studied in an abstract way. Instead than relying just on theoretical explanations in the classroom, students gain a tangible understanding of the ideas of physical and chemical changes through these observations and hands-on activities. Additionally, the liquid smoke experiment incorporates a number of scientific ideas, including physical and chemical changes as well as the function of chemical compounds in everyday life. Learning becomes more relevant and contextual as a result.

Overall, the comparative quantitative analysis demonstrates that differences in antibacterial potential between pyrolysis and distillation fractions are primarily attributable to relative enrichment and depletion of compound classes, rather than absolute presence or absence of specific molecules. This process–composition relationship provides a mechanistic framework for selecting appropriate biomass processing routes based on desired functional properties, while highlighting the need for future studies to integrate standardized biological testing to validate these chemically inferred mechanisms.

CONCLUSION

Fundamental Finding: This study confirms that pyrolysis and distillation generate chemically distinct liquid smoke fractions from teak (*Tectona grandis*) sawdust, demonstrating that processing pathways strongly influence functional compound distribution. Pyrolysis produced liquid smoke enriched in organic acids (≈35%) and chemically diverse reactive compounds, resulting in lower pH and a composition inferred to support stronger antibacterial potential. In contrast, distillation selectively concentrated thermally stable phenolic compounds (≈40%), such as guaiacol, cresol, and syringol, while reducing highly volatile constituents and polycyclic aromatic hydrocarbons (PAHs). **Implication:** These findings highlight route-specific application potential. Pyrolysis-derived liquid smoke is more suitable for food preservation, agricultural sanitation, and post-harvest microbial control, where strong antimicrobial action is required. Distillation-derived liquid smoke offers advantages for personal care products, cosmetic preservatives, and household antiseptics, where chemical stability and controlled activity are essential. **Limitation:** This study focuses on chemical profiling and inferred antibacterial mechanisms and does not include standardized microbiological assays or process optimization. **Future Research:** Future studies should integrate quantitative antimicrobial testing, toxicity assessment, and optimization of processing conditions to validate application-specific performance and support scalable biomass valorization.

REFERENCES

Asdaq, S. M. B., Nayeem, N., Abida, Alam, M. T., Alaqel, S. I., Imran, M., Hassan, E. W. E., & Rabbani, S. I. (2022). *Tectona grandis* L.f.: A comprehensive review on its patents, chemical constituents, and biological activities. *Saudi Journal of Biological Sciences, 29*(3), 1456–1464. https://doi.org/10.1016/j.sjbs.2021.11.026

Budianto, B., Inayah, N., Fatmaningrum, F., & Suparmi, A. (2021). Comparison of the effectiveness of leaf extracts of *Anredera cordifolia*, *Psidium guajava*, and *Pogostemon cablin* on inhibitory power over *Escherichia coli* bacteria. *Vitae, 28*(3). https://doi.org/10.17533/udea.vitae.v28n3a345386

Budianto, K., Arumsari, A. G., Budiman, Y. A., Riswari, M., & Umami, R. (2025). Biochemical composition and proteolytic activity of *Cymbopogon citratus* protease. *Journal of Microbiology, Biotechnology and Food Sciences, 15*(1), e12091. https://doi.org/10.55251/jmbfs.12091

Charoensit, P., Sawasdipol, F., Tibkawin, N., Suphrom, N., & Khorana, N. (2021). Development of natural pigments from *Tectona grandis* (teak) leaves: Agricultural waste material from teak plantations. *Sustainable Chemistry and Pharmacy, 19*, 100365. https://doi.org/10.1016/j.scp.2020.100365

da Paixão Cansado, I. P., Mourão, P. A. M., & Belo, C. R. (2022). Using *Tectona grandis* biomass to produce valuable adsorbents for pesticide removal from liquid effluent. *Materials, 15*(17), 5842. https://doi.org/10.3390/ma15175842

de Castro, V. R., Surdi, P. G., Fernandes, S. A., da Silva Berger, M., Vinha Zanuncio, A. J., Zanuncio, J. C., & de Oliveira Araujo, S. (2022). Chemical composition of heartwood and sapwood of *Tectona grandis* characterized by CG/MS-PY. *Scientific Reports, 12*(1), 18441. https://doi.org/10.1038/s41598-022-22800-1

El Farissi, H., Talhaoui, A., & El Bachiri, A. (2022). Influence of pyrolysis process on the production of bio-oil used as alternative green energy from *Pistacia lentiscus* L. *Journal of Analytical and Applied Pyrolysis, 168*, 105781. https://doi.org/10.1016/j.jaap.2022.105781

Elhenawy, Y., Fouad, K., Mansi, A., Bassyouni, M., Gadalla, M., Ashour, F., & Majozi, T. (2024). Experimental analysis and numerical simulation of biomass pyrolysis. *Journal of Thermal Analysis and Calorimetry, 149*(19), 10369–10383. https://doi.org/10.1007/s10973-024-12987-y

Elkasabi, Y., Jones, K., Mullen, C. A., Strahan, G. D., & Wyatt, V. T. (2023). Spinning band distillation of biomass pyrolysis oil phenolics to produce pure phenol. *Separation and Purification Technology, 314*, 123603. https://doi.org/10.1016/j.seppur.2023.123603

Firdaus Mohamad Yusop, M., Aziz, A., & Azmier Ahmad, M. (2022). Conversion of teak wood waste into microwave-irradiated activated carbon for cationic methylene blue dye removal: Optimization and batch studies. *Arabian Journal of Chemistry, 15*(9), 104081. https://doi.org/10.1016/j.arabjc.2022.104081

Gama, G. S. P., Pimenta, A. S., Feijó, F. M. C., Azevedo, T. K. B. de, Melo, R. R. de, & Andrade, G. S. de. (2024). The potential of wood vinegar to replace antimicrobials used in animal husbandry: A review. *Animals, 14*(3), 381. https://doi.org/10.3390/ani14030381

Gani, A., Adlim, M., Rahmayani, R. F. I., Hanum, L., & Nabila, R. (2024). Preparation and characterization of coconut shell liquid smoke and the properties of preserving tofu. *Kuwait Journal of Science, 51*(4), 100289. https://doi.org/10.1016/j.kjs.2024.100289

Guo, T., Wang, Z., Tang, W., Wang, W., Bi, F., Wang, B., Zhou, Z., Meng, Z., & Ge, Z. (2018). A good balance between the energy density and sensitivity from assembly of bis(dinitromethyl) and bis(fluorodinitromethyl) with a single furazan ring. *Journal of Analytical and Applied Pyrolysis, 134*, 218–230. https://doi.org/10.1016/j.jaap.2018.06.012

Haq, N. U., Liaquat, M., Alharby, H. F., & Alzahrani, Y. M. (2022). Optimization and purification of terpenyl flavor esters catalyzed by black cumin (*Nigella sativa*) seedling lipase in organic media. *Frontiers in Sustainable Food Systems, 6*, 915602. https://doi.org/10.3389/fsufs.2022.915602

Haryanto, A., Hidayat, W., Hasanudin, U., Iryani, D. A., Kim, S., Lee, S., & Yoo, J. (2021). Valorization of Indonesian wood wastes through pyrolysis: A review. *Energies, 14*(5), 1407. https://doi.org/10.3390/en14051407

Hidayatullah, N., Suandy, I., Intanon, M., Alter, T., Susanti, O., Herpianti, A., Susanty, S., Desitania, R., & Awaiwanont, N. (2025). Occurrence and molecular characterization of extended-spectrum beta-lactamase-producing *Escherichia coli* in broilers in Indonesia. *Antibiotics, 14*(10), 1030. https://doi.org/10.3390/antibiotics14101030

Ilsan, N. A., Yunita, M., Dewi, N. K., Irham, L. M., Sipriyadi, Nurfajriah, S., & Inggraini, M. (2023). Potentially virulent multidrug-resistant *Escherichia fergusonii* isolated from inanimate surfaces in a medical university: *Omphisa fuscidentalis* as an alternative for bacterial virulence determination. *Diagnostics, 13*(2), 279. https://doi.org/10.3390/diagnostics13020279

Jerzak, W., Acha, E., & Li, B. (2024). Comprehensive review of biomass pyrolysis: Conventional and advanced technologies, reactor designs, product compositions and yields, and techno-economic analysis. *Energies, 17*(20), 5082. https://doi.org/10.3390/en17205082

Liao, S., Sun, W., Zheng, H., & Xu, Q. (2025). Source tracing of raw material components in wood vinegar distillation process based on machine learning and Aspen simulation. *ChemEngineering, 9*(2), 32. https://doi.org/10.3390/chemengineering9020032

Mashuni, M., Kadidae, L. O., Jahiding, M., Hamid, F. H., Abdul, W., Muhammad, A., & Khaeri, N. (2024). Chemical characterization and antibacterial activities of bio-oil from durian shell pyrolysis. *Jurnal Kimia Valensi, 10*(1), 86–96. https://doi.org/10.15408/jkv.v10i1.37674

Mati, A., Buffi, M., Dell'Orco, S., Lombardi, G., Ruiz Ramiro, P. M., Kersten, S. R. A., & Chiaramonti, D. (2022). Fractional condensation of fast pyrolysis bio-oil to improve biocrude quality towards alternative fuels production. *Applied Sciences, 12*(10), 4822. https://doi.org/10.3390/app12104822

NIST. (2014). *NIST/EPA/NIH mass spectral library* (NIST Standard Reference Database No. 69). NIST Mass Spectrometry Data Center.

Peh, E., Kittler, S., Reich, F., & Kehrenberg, C. (2020). Antimicrobial activity of organic acids against *Campylobacter* spp. and development of combinations—A synergistic effect? *PLOS ONE, 15*(9), e0239312. https://doi.org/10.1371/journal.pone.0239312

Pramono, A. P., Amru, B. A., Rahmani, H. A., Fernanda, S. A., Nugraha, Y., Ramadhan, M. Y. A., Harahap, A. F. P., Fauzantoro, A., Irsyad, N. S., & Bahar, M. (2022). *Nicotiana tabacum* var. Virginia bio-oil-based pyrolysis extraction has prominent antimicrobial potential compared to ethanol heat reflux extraction. *HAYATI Journal of Biosciences, 29*(4), 515–525. https://doi.org/10.4308/hjb.29.4.515-525

Puvača, N., Milenković, J., Galonja Coghill, T., Bursić, V., Petrović, A., Tanasković, S., Pelić, M., Ljubojević Pelić, D., & Miljković, T. (2021). Antimicrobial activity of selected essential oils against selected pathogenic bacteria: In vitro study. *Antibiotics, 10*(5), 546. https://doi.org/10.3390/antibiotics10050546

Rizal, W. A., Wahono, S. K., & Yuliansyah, A. T. (2024). Enhancing wood vinegar quality: Integrated pyrolysis process of cajuput (*Melaleuca leucadendron*) twigs biomass with gas-phase adsorption using zeolite adsorbents. *Bioresource Technology Reports, 26*, 101840. https://doi.org/10.1016/j.biteb.2024.101840

Singh, J., & Mishra, V. (2021). Synthesis and characterization of activated carbon derived from *Tectona grandis* sawdust via green route. *Environmental Progress & Sustainable Energy, 40*(2), e13525. https://doi.org/10.1002/ep.13525

Sokamte, A., Desire, P., Manjabhat, N., Forestine, N., Nodem, D., & Tatsadjieu, L. (2020). Characterization of volatile compounds of liquid smoke flavourings from some tropical hardwoods. *Scientific African, 8*, e00443. https://doi.org/10.1016/j.sciaf.2020.e00443

Vidic, D., Čopra-Janićijević, A., Miloš, M., & Maksimović, M. (2018). Effects of different methods of isolation on volatile composition of *Artemisia annua* L. *International Journal of Analytical Chemistry, 2018*, 9604183. https://doi.org/10.1155/2018/9604183

Vyas, P., Yadav, D., & Khandelwal, P. (2019). *Tectona grandis* (teak): A review on its phytochemical and therapeutic potential. *Natural Product Research, 33*(1), 1–17. https://doi.org/10.1080/14786419.2018.1440217

***Yudanti (Corresponding Author)**
Department of Sains Education,
Universitas Negeri Surabaya
Address: Komplek Universitas Negeri Surabaya Gedung D1, Jl. Ketintang Sel. Kec. Gayungan, Surabaya, Jawa Timur 60231
Email: yudanti47@guru.smk.belajar.id

Rudiana Agustini
Department of Sains Education,
Universitas Negeri Surabaya
Address: Komplek Universitas Negeri Surabaya Gedung D1, Jl. Ketintang Sel. Kec. Gayungan, Surabaya, Jawa Timur 60231
Email: rudianaagustini@unesa.ac.id

Zainul Arifin Imam Supardi
Department of Physics,
Universitas Negeri Surabaya
Address: Komplek Universitas Negeri Surabaya Gedung D1, Jl. Ketintang Sel. Kec. Gayungan, Surabaya, Jawa Timur 60231
Email: zainularifin@unesa.ac.id