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Coal-derived liquid smoke as an eco-friendly coagulant for enhancing the quality of natural latex in Jambi, Indonesia

Muhammad Naswir[1], Intan Lestari[1], Jalius[1], Yudha Gusti Wibowo[2*]

[1] Program Study of Chemistry, Faculty of Science and Technology, Universitas Jambi, Jambi, Indonesia
[2] Department of Mining Engineering, Institut Teknologi Sumatera, Lampung, Indonesia
* Corresponding author's e-mail: m.naswir@yahoo.com

ABSTRACT

The productivity and quality of natural rubber in Indonesia, particularly in Jambi Province, remain suboptimal, resulting in lower market value compared to rubber from Malaysia and Thailand. This study investigates the potential of coal-derived liquid smoke as an alternative coagulant to improve the quality of natural latex. Liquid smoke was produced using a 3-in-1 pyrolysis reactor operated at 250–300 °C for 5 hours and subsequently purified into three grades. Various concentrations (10%, 25%, 45%, 50%, and 60%) of liquid smoke were tested for latex coagulation. Characterization revealed that purified liquid smoke had a pH range of 2.06–2.66, total phenolic content of 11.67–13.13 mg GAE/100 g, and acidity of 11.12–13.06%. Field applications with local farmers in Ladang Panjang Village demonstrated that liquid smoke at concentrations above 40% significantly improved latex quality, with faster coagulation times, reduced impurities, and enhanced resistance to microbial growth. These findings suggest that coal-derived liquid smoke is a cost-effective, environmentally friendly alternative to conventional coagulants, contributing to improved rubber quality and market value.

Keywords: liquid smoke, pyrolysis, latex coagulation, natural rubber, sustainability.

INTRODUCTION

Natural rubber is an essential agricultural commodity and a major contributor to Indonesia's economy, particularly in Jambi Province, where rubber plantations cover approximately 667,114 hectares and provide employment for over 250,000 workers (Achmad et al., 2020). Despite its economic significance, the quality of natural rubber from Indonesia lags behind that of Malaysia and Thailand, reducing its competitiveness in the global market (Hardiwan et al., 2019). Addressing this quality gap is vital for enhancing the value and marketability of Indonesian rubber. Traditional latex coagulation processes primarily utilize acetic acid or formic acid. While effective, these chemicals present several challenges, including high costs, environmental harm, and the production of unpleasant odors in the final rubber product. Consequently, there is an urgent need for cost-effective and eco-friendly alternatives to improve latex quality while addressing sustainability concerns (Gea et al., 2018).

One promising alternative is liquid smoke, a byproduct of pyrolysis. Liquid smoke derived from agricultural and forestry biomass – such as coconut shells, palm kernel shells, and wood – contains phenolic and acidic compounds with antimicrobial and antioxidant properties (Afrah et al., 2024; Santiyo Wibowo et al., 2023; Surboyo et al., 2024; Winarni et al., 2021). These properties make it suitable for various applications, including food preservation and latex coagulation (Evahelda et al., 2021; Lingbeck et al., 2014). Studies have shown that liquid smoke can enhance the efficiency of latex coagulation and improve the physical and chemical properties of rubber (Wibowo et al., 2016). However, existing research has primarily focused on biomass-derived liquid smoke, leaving significant gaps in exploring alternative feedstocks, such as coal.

Coal, which is abundant in Indonesia, particularly in Jambi, presents an untapped opportunity for liquid smoke production. Compared to biomass, coal-derived liquid smoke offers consistent quality and greater scalability, making it a potentially reliable coagulant for latex production. Despite these advantages, coal's potential as a feedstock for liquid smoke production has been underutilized. Moreover, while the chemical properties of liquid smoke have been studied, its field performance and impact on the rubber market remain largely unexplored. This highlights the need to investigate coal-derived liquid smoke as an innovative solution to improve latex quality and enhance sustainability in rubber production.

This study aims to address these gaps by developing and evaluating coal-derived liquid smoke as an eco-friendly coagulant for natural latex. Specifically, the objectives are to:
1) produce and purify liquid smoke from coal using a 3-in-1 pyrolysis reactor and analyze its chemical properties;
2) assess the effectiveness of coal-derived liquid smoke in coagulating natural latex at varying concentrations;
3) evaluate its field application in improving latex quality and market value through collaboration with local farmers in Jambi;
4) contribute to sustainable rubber production by providing an environmentally friendly and cost-effective alternative to conventional chemical coagulants.

By advancing coal-derived liquid smoke as a novel solution, this study seeks to bridge the gap between environmental sustainability and economic viability in Indonesia's rubber industry, enhancing its global competitiveness and promoting sustainable development in the region.

METHODS

Study design

This study consisted of three main stages: the production of liquid smoke from subbituminous coal using a 3-in-1 pyrolysis reactor, the characterization of its chemical properties, and the evaluation of its performance in latex coagulation. The research was conducted in both laboratory and field settings, ensuring a comprehensive assessment of the liquid smoke's effectiveness. Field trials were carried out in collaboration with farmers in Ladang Panjang Village, Muaro Jambi.

Materials

Subbituminous coal, obtained from Ness Village in Muaro Jambi, Indonesia, was used as the primary raw material due to its low moisture content, which enhances the efficiency of pyrolysis. Other materials included hydrochloric acid (HCl), sulfuric acid (H_2SO_4), buffer solutions (pH 4 and pH 9), phenol reagents, and distilled water for purification and characterization processes. Natural latex was sourced from rubber plantations in Ladang Panjang Village.

The equipment used included a 3-in-1 pyrolysis reactor, a pH meter for acidity measurements, a gas chromatography-mass spectrometry (GC-MS) system for chemical composition analysis, and a UV-Vis spectrophotometer for phenol content determination. Scanning electron microscopy (SEM) was employed to analyze the microstructure of the coagulated latex, along with standard laboratory tools such as an analytical balance, distillation units, and routine glassware.

Preparation of coal-derived liquid smoke

The preparation process began with the crushing and sieving of coal to a particle size of 150–200 mesh to ensure uniform pyrolysis. A batch of 100 kg of coal was loaded into the pyrolysis reactor, which was heated to a temperature range of 250–300 °C for 5 hours. The vapors generated during this process were condensed in a coiled condenser, resulting in three byproducts: liquid smoke, tar, and charcoal.

The crude liquid smoke was then purified through fractional distillation into three grades based on boiling points: Grade III (110–120 °C), Grade II (130–145 °C), and Grade I (170–190 °C). The distilled liquid smoke was allowed to settle for three days to separate any residual solids before being stored in sealed containers for further analysis and application.

Characterization of liquid smoke

The chemical properties of the liquid smoke were characterized through a series of analytical techniques. The pH of each grade was measured using a calibrated pH meter. Total acidity was determined by titration with a standard NaOH solution, and the phenolic content was quantified using the Folin-Ciocalteu method. The phenolic content was expressed as mg of gallic acid equivalent (GAE) per 100 g of liquid smoke. Gas chromatography-mass spectrometry (GC-MS) was used to identify and quantify key components such as acetic acid and phenolic compounds, which contribute to the coagulation and antimicrobial properties of the liquid smoke.

Latex coagulation trials

Laboratory experiments were conducted to evaluate the coagulation efficiency of liquid smoke at varying concentrations. Natural latex (135 mL) was mixed with liquid smoke at concentrations of 10%, 25%, 45%, 50%, and 60% in separate beakers. The coagulation time was recorded, and the physical properties of the resulting rubber, including texture and color, were visually inspected. Control samples, including latex without a coagulant and latex treated with acetic acid, were used for comparison.

Field trials were conducted with the Karang Sari farmer group in Ladang Panjang Village to validate the laboratory results under real-world conditions. The liquid smoke was used to coagulate latex collected from local rubber trees, and the coagulated rubber was assessed for quality improvement and market value.

Analysis of coagulated latex

The physical and chemical properties of the coagulated latex were analyzed according to the Indonesian National Standard (SNI-06-1903-2000) for rubber. The analyses included the measurement of volatile content, ash content, and dirt levels. SEM was used to examine the microstructure of the coagulated latex, comparing samples treated with liquid smoke to those treated with conventional coagulants or left untreated.

The physical inspection included assessments of texture, color, and microbial resistance during storage. Samples were observed over five days to determine their susceptibility to microbial growth, such as maggots, which are indicative of poor-quality latex. The results were used to evaluate the overall effectiveness of coal-derived liquid smoke as a latex coagulant.

RESULT AND DISCUSSION

Preparation of liquid smoke and reactor optimization

The production of liquid smoke from subbituminous coal was conducted using a 3-in-1 pyrolysis reactor, which was optimized to enhance efficiency and yield. The reactor underwent necessary repairs to components such as the combustion chamber and condensation system, ensuring effective operation. The pyrolysis process was carried out at temperatures ranging from 250 to 300 °C over a period of 4.5 to 5 hours, resulting in the production of liquid smoke, tar, and charcoal. From 100 kg of coal, approximately 12 liters of liquid smoke were obtained, which were subsequently purified into three distinct grades based on boiling point ranges: Grade III (110–120 °C), Grade II (130–145 °C), and Grade I (170–190 °C). The preparation of liquid smoke can be seen in Figure 1. The selection of subbituminous coal as the feedstock was strategic,

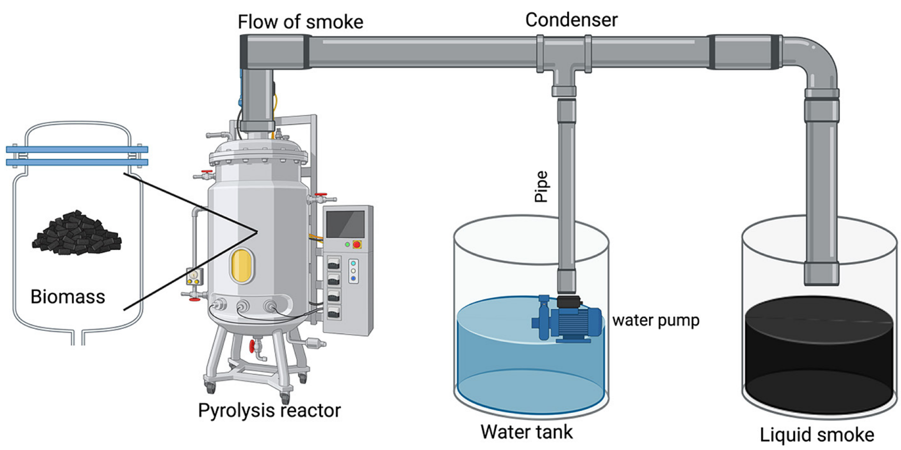

Figure 1. Production of liquid smoke from coal

considering its lower moisture content and higher carbon concentration compared to lignite, which enhances pyrolysis efficiency. The choice of feedstock significantly influences the quality and composition of the resulting liquid smoke. Studies have shown that the chemical composition of pyrolysis oils depends on several factors, including the type of biomass and pyrolysis conditions (Basafa & Hawboldt, 2023). In this context, coal-derived liquid smoke offers a more consistent composition compared to biomass-derived alternatives, which can vary due to the heterogeneous nature of biomass feedstocks.

The pyrolysis temperature range of 250–300 °C was selected to optimize the breakdown of coal's organic compounds into volatile substances, including phenols and acetic acid. This temperature range is critical, as it influences the yield and quality of pyrolysis products. Rapid heating and cooling of primary vapors are required to minimize secondary reactions that can reduce liquid yield and negatively impact its quality (Varma et al., 2018). Therefore, maintaining the appropriate temperature and heating rates is essential for producing high-quality liquid smoke.

The purification of liquid smoke through fractional distillation into three grades showed in Figure 2. The high yield of Grade I liquid smoke suggests effective separation and concentration of desired compounds. The chemical composition of pyrolysis oils, including liquid smoke, depends on several factors such as type of biomass, feedstock pre-treatment, and pyrolysis conditions (Basafa & Hawboldt, 2023). Therefore, the purification process is crucial in standardizing the quality of the final product.

Comparatively, biomass-derived liquid smoke often exhibits variability in composition due to differences in feedstock characteristics and pyrolysis conditions. For instance, the chemical composition of liquid smoke can vary based on the type of biomass used and the conditions under which pyrolysis is conducted (Xin et al., 2021). This variability can affect the consistency and efficacy of the liquid smoke in applications such as latex coagulation. In contrast, coal-derived liquid smoke offers a more uniform composition, which can be advantageous in industrial applications requiring consistent quality.

The utilization of subbituminous coal for liquid smoke production represents a sustainable approach, leveraging local resources and providing an alternative use for coal beyond energy combustion. This method contributes to waste minimization and adds value to coal resources. Additionally, the integration of liquid smoke production into existing industrial processes enhances its economic feasibility. For example, liquid smoke derived from pyrolysis has shown potential as an effective latex coagulant and offers environmental benefits by reducing waste and improving product quality (Sinaga et al., 2023).

The preparation of liquid smoke from subbituminous coal using an optimized pyrolysis reactor demonstrates effective production and purification processes. Controlled pyrolysis conditions ensure high yields and consistent quality, as observed in similar processes involving coal and biomass-derived liquid smoke (Adiningsih et al., 2021). This method surpasses biomass-derived alternatives in terms of uniformity and scalability, making it a viable option for industrial applications such as natural latex coagulation.

Characterization of liquid smoke

The chemical characterization of coal-derived liquid smoke revealed its substantial potential as an effective coagulant for natural latex, primarily due to its acidity and phenolic content. Comprehensive analysis, including pH measurements, total acidity, phenolic content determination, and Gas Chromatography-Mass Spectrometry (GC-MS), provided insights into the functional components responsible for its coagulation and antimicrobial properties. Figure 3 illustrates the production and characterization process of liquid smoke

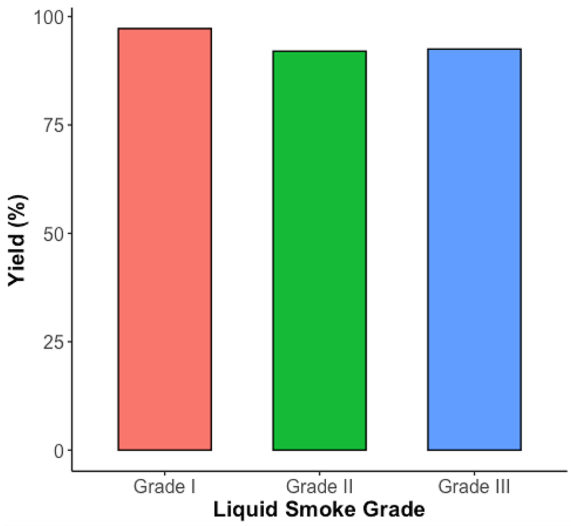

Figure 2. Yield of liquid smoke

derived from coal. Figure 3a presents the 3-in-1 liquid smoke production system, which integrates pyrolysis, condensation, and collection in a single setup. This system efficiently converts coal into liquid smoke through thermal decomposition and subsequent condensation of the generated vapors. Figure 3b provides a close-up view of the liquid smoke outlet from the reactor, showcasing the collection process where the condensed liquid smoke is directed into storage containers. This step is crucial in ensuring the proper separation and collection of liquid smoke fractions. Figure 3(c) displays bottled liquid smoke samples before transportation to the laboratory for further analysis. These samples are categorized based on their physical characteristics, such as color and viscosity, which may indicate differences in chemical composition. Figure 3d shows the liquid smoke contained in an Erlenmeyer flask before undergoing characterization, where its chemical and physical properties will be analyzed.

The chemical properties of liquid smoke showed in Figure 4. These findings align with those of the previous study (Evahelda et al., 2021), who observed that higher acidity enhances coagulation efficiency and antimicrobial properties in liquid smoke. The acidity of liquid smoke accelerates latex coagulation by destabilizing the colloidal suspension of rubber particles, as corroborated by Adiningsih et al. (2021), who found that optimal acidic conditions result in improved latex coagulation.

The phenolic content of coal-derived liquid smoke further enhances its functionality. Measured in terms of gallic acid equivalent (GAE) per 100 g, phenolic content ranged from 10.53 mg GAE/100 g in Grade III to 13.13 mg GAE/100 g in Grade I. Phenolic compounds, such as guaiacol, cresols, and syringol derivatives identified in GC-MS analysis, are known for their antimicrobial properties. These compounds disrupt microbial cell membranes, thereby preventing bacterial growth and spoilage in coagulated latex. Previous studies, including those by Vachlepi & Suwardin (2015), have emphasized the role of phenolic compounds in improving the preservation and antimicrobial benefits of liquid smoke.

GC-MS analysis further highlighted the chemical composition of coal-derived liquid smoke, with acetic acid and phenolic compounds as dominant components. Acetic acid constituted the majority of the acidic content, while phenolic compounds contributed to both coagulation efficiency and microbial inhibition. These results align with prior studies on the pyrolysis of organic materials, such as those by Wibowo et al. (2016), which consistently identified acetic acid and phenols as key contributors to the efficacy of liquid smoke.

When compared to biomass-derived liquid smoke, coal-derived liquid smoke demonstrated comparable or superior characteristics. For example, a previous study reported that coal-derived liquid smoke offers greater consistency and

Figure 3. (a) 3 in 1 technology; (b) liquid smoke in outlet; (c) liquid smoke in the bottle; (d) liquid smoke before characterization

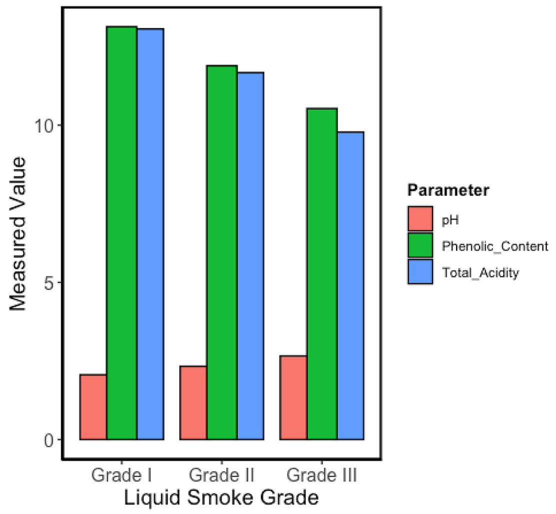

Figure 4. Chemical properties of liquid smoke

scalability, making it ideal for industrial-scale latex production (Evahelda et al., 2021). The higher phenolic content and acidity of coal-derived liquid smoke enhance its suitability for industrial applications, offering both improved coagulation and extended product shelf life.

Thus, the chemical characterization of coal-derived liquid smoke underscores its potential as an effective and sustainable coagulant for natural latex production. Its high acidity and phenolic content ensure rapid coagulation and microbial inhibition, while its consistent chemical composition supports large-scale applications. These attributes make it a viable and environmentally friendly alternative to conventional coagulants.

Analysis of dirt content, ash content, and volatile matter

The results of this study demonstrate that liquid smoke, particularly coal-derived liquid smoke, serves as an effective coagulant for natural latex by significantly reducing impurities, such as dirt content, ash content, and volatile matter. In this study, Grade III liquid smoke was selected for further analysis due to its superior performance in coagulating natural latex. The liquid smoke was distilled into three grades (Grade I, II, and III), with Grade III obtained at 110–120°C, producing the highest yield (92.5%) compared to Grade II (92%) and Grade I (97.22%). The high yield of Grade III makes it more abundant and economically feasible for large-scale application. Experimental results demonstrated that Grade III liquid smoke effectively coagulated latex at various concentrations (10%, 25%, 45%, 50%, and 60%), with optimal results observed at concentrations ≥40%. The coagulation process using Grade III was significantly faster, taking only 5–7 minutes, whereas non-graded liquid smoke required a longer time. This efficiency can be attributed to the higher acetic acid and phenolic compound content in Grade III, which are crucial for the coagulation process. Additionally, its low pH (2.06–2.58) enhances coagulation efficiency while also preventing bacterial contamination in latex.

Latex treated with Grade III liquid smoke exhibited superior quality, as evidenced by its lower impurity content, specifically dirt content (0.060%), ash content (0.020%), and volatile matter (0.025%). The treated latex formed a denser and cleaner rubber matrix, contributing to better mechanical properties and higher market value. Furthermore, the antibacterial and antioxidant properties of Grade III liquid smoke prevented microbial growth, reducing the risk of bacterial decomposition and unpleasant odors in latex. The effectiveness of Grade III liquid smoke was further validated through field application trials in Desa Ladang Panjang, Jambi, where farmers reported enhanced latex quality and increased selling prices. Given its optimal coagulation efficiency, latex quality improvement, microbial resistance, and economic feasibility, Grade III liquid smoke is the most suitable candidate for replacing conventional coagulating agents like acetic and formic acid in latex processing.

Figure 5 showcases the performance of both Grade III and non-graded liquid smoke, highlighting that concentrations of 45% or higher are optimal for achieving high-quality latex. These

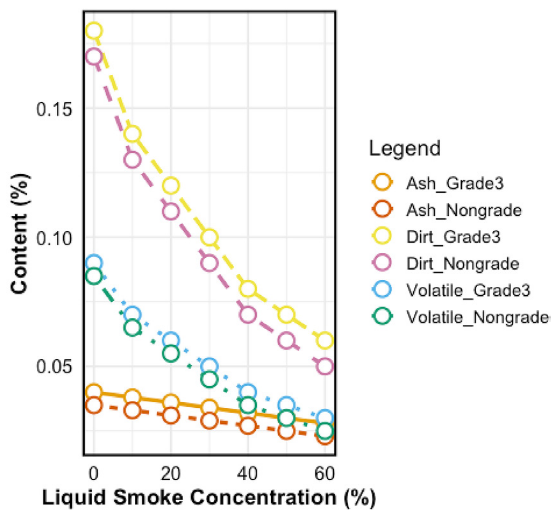

Figure 5. Liquid smoke characteristics

findings align with previous research indicating the suitability of liquid smoke in meeting stringent quality standards for rubber production (Sinaga et al., 2023). Latex coagulated with Grade III liquid smoke at concentrations of 10%, 25%, 45%, 50%, and 60% exhibited dirt contents of 0.068%, 0.060%, and below 0.2%, meeting the requirements of the Indonesian National Standard (SNI 06-1903-2000) for standard indonesian rubber (SIR). In contrast, untreated latex showed significantly higher dirt content, failing to meet these standards. Non-graded liquid smoke also reduced dirt content but was slightly less effective than Grade III liquid smoke (Wibowo et al., 2016). The reduction in dirt content is attributed to the acidic and phenolic compounds in liquid smoke, which destabilize impurities, making them easier to separate from the rubber matrix (Evahelda et al., 2021). The ash content of latex coagulated with Grade III liquid smoke consistently remained below 1%, even at lower concentrations, and decreased further with higher liquid smoke concentrations. For example, at a 45% concentration, ash content was measured at 0.060%, compared to 0.058% in untreated latex. These levels are compliant with SNI standards, underscoring the ability of liquid smoke to maintain minimal inorganic residue levels. Non-graded liquid smoke also reduced ash content but was less effective, likely due to lower concentrations of phenolic and acidic compounds.

Volatile matter levels were significantly reduced in latex coagulated with liquid smoke compared to untreated latex. For Grade III liquid smoke, volatile matter decreased from 0.037% at a 10% concentration to 0.010% at a 60% concentration. Although non-graded liquid smoke also reduced volatile matter, its performance was inferior to that of Grade III liquid smoke. Untreated latex exhibited volatile matter levels exceeding 0.08%, which is associated with lower-quality rubber prone to unpleasant odors and microbial growth. Reducing volatile matter is critical for improving rubber quality and durability. Elevated levels of volatile matter can lead to odors and promote microbial activity, accelerating degradation during storage. The ability of liquid smoke to lower volatile matter can be attributed to its antimicrobial properties, primarily derived from phenolic compounds and acetic acid. The reduction in dirt content, ash content, and volatile matter significantly enhances the overall quality of coagulated latex. Cleaner, impurity-free rubber exhibits superior mechanical properties, such as higher elasticity and tensile strength, which are crucial for industrial applications. Additionally, lower volatile matter levels ensure odor-free rubber that resists microbial spoilage during storage and transportation.

Use of liquid smoke for latex coagulation

The effect of coal-derived liquid smoke concentration on latex coagulation time, visual properties, and microbial resistance was investigated. The findings demonstrated that both Grade III and non-graded liquid smoke significantly influenced the coagulation process, with higher concentrations producing faster coagulation times and better-quality latex. The coagulation time decreased with increasing concentrations of liquid smoke, as shown in Figure 6. For latex treated with Grade III liquid smoke, the coagulation time decreased significantly to just 6 minutes at 60% concentration, compared to 53 minutes at 10%. At intermediate concentrations of 25% and 45%, coagulation times were 9 minutes 12 seconds and 7 minutes 32 seconds, respectively. Conversely, latex treated with non-graded liquid smoke exhibited longer coagulation times across all concentrations. At 60%, 50%, and 45%, the coagulation times were recorded as 15 minutes 27 seconds, 16 minutes, and 16 minutes 70 seconds, respectively. At lower concentrations, such as 10% and 25%, the coagulation times increased to 37 minutes and 20 minutes 19 seconds, respectively.

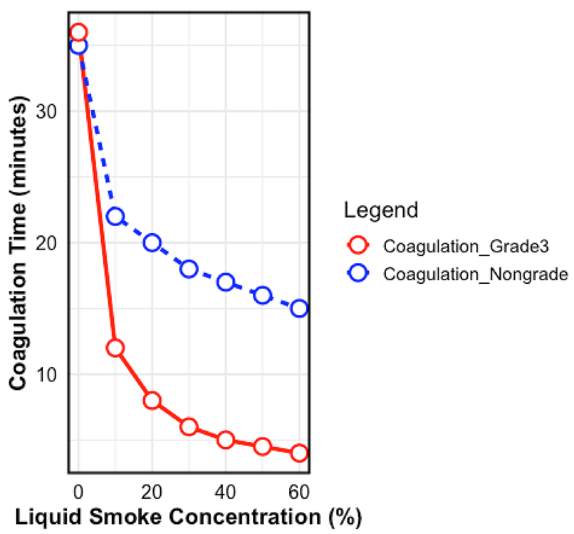

Figure 6. Effect of liquid smoke concentration with coagulation times

The faster coagulation observed with Grade III liquid smoke can be attributed to its higher concentration of phenolic and acidic compounds, particularly acetic acid, which accelerates the destabilization of colloidal rubber particles in the latex. This result aligns with Ompusunggu (1995), who emphasized that acidic conditions promote coagulation efficiency while preserving the plasticity retention index (PRI). The lower pH values of higher-concentration liquid smoke create an environment conducive to rapid coagulation, minimizing coagulum formation time (Milly et al., 2005).

The visual properties of the coagulated latex also varied depending on the grade and concentration of liquid smoke, as presented in Figures 7a and 7b. Latex coagulated with Grade III liquid smoke at concentrations above 25% exhibited a white to light-yellow color, indicating a cleaner coagulum with fewer impurities. In contrast, latex treated with non-graded liquid smoke displayed a light-yellow to brownish color, especially at lower concentrations. The darker appearance of non-graded liquid smoke coagulum can be attributed to residual impurities and a lower concentration of phenolic compounds, which result in incomplete reactions with metal ions present in latex. Over time, as water evaporated from the coagulum, its color deepened to brown or black, a phenomenon explained by the interaction of phenolic compounds with metal ions. According to Ompusunggu (1995), coagulation at very low pH values ensures rapid coagulation but can lead to darker-colored rubber, which may affect its modulus properties (Soares et al., 2016).

The microbial resistance of coagulated latex was closely associated with the concentration of phenolic and acidic compounds present in the liquid smoke. Figure 8a– 5f clearly illustrate the differences in microbial activity based on liquid smoke treatments. Latex treated with low concentrations, particularly 10% Grade III and non-graded liquid smoke, showed visible microbial spoilage after five days of storage, resulting in the appearance of maggots on the latex surface. Untreated latex samples (Figure A) exhibited the most severe microbial growth, further confirming the necessity of coagulants with antimicrobial properties to maintain latex quality (Soares et al., 2016).

For latex treated with non-graded liquid smoke at 25% concentration (Figures D and E), microbial activity persisted, as evidenced by significant larval infestation. These results indicate that at lower concentrations, non-graded liquid smoke lacks sufficient phenolic and acidic content to inhibit bacterial proliferation effectively. In contrast, Grade III liquid smoke at concentrations of 45% or higher demonstrated excellent antimicrobial properties, with no visible microbial growth observed after the storage period.

The antimicrobial efficacy of liquid smoke can be attributed to its phenolic compounds and acetic acid. Phenols disrupt microbial cell membranes, leading to cell lysis, while acetic acid lowers the pH, creating an environment unsuitable for bacterial growth. These findings are consistent with previous study which highlighted the role of phenolic compounds as natural antibacterial agents (Kim et al., 2018). Additionally, other study demonstrated the efficacy of liquid smoke in preserving organic materials by inhibiting microbial growth, further supporting these results (Holley & Patel, 2005).

Visually, the latex treated with 10% Grade III and non-graded liquid smoke developed a greyish-brown appearance (Figures B and C), indicating microbial degradation. In contrast, samples

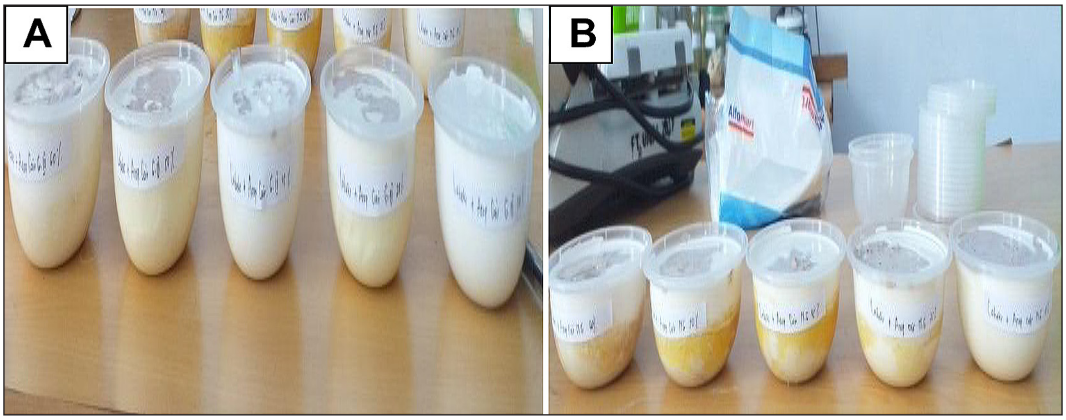

Figure 7. Latex coagulation using grade 3 (a) vs non-grade (b)

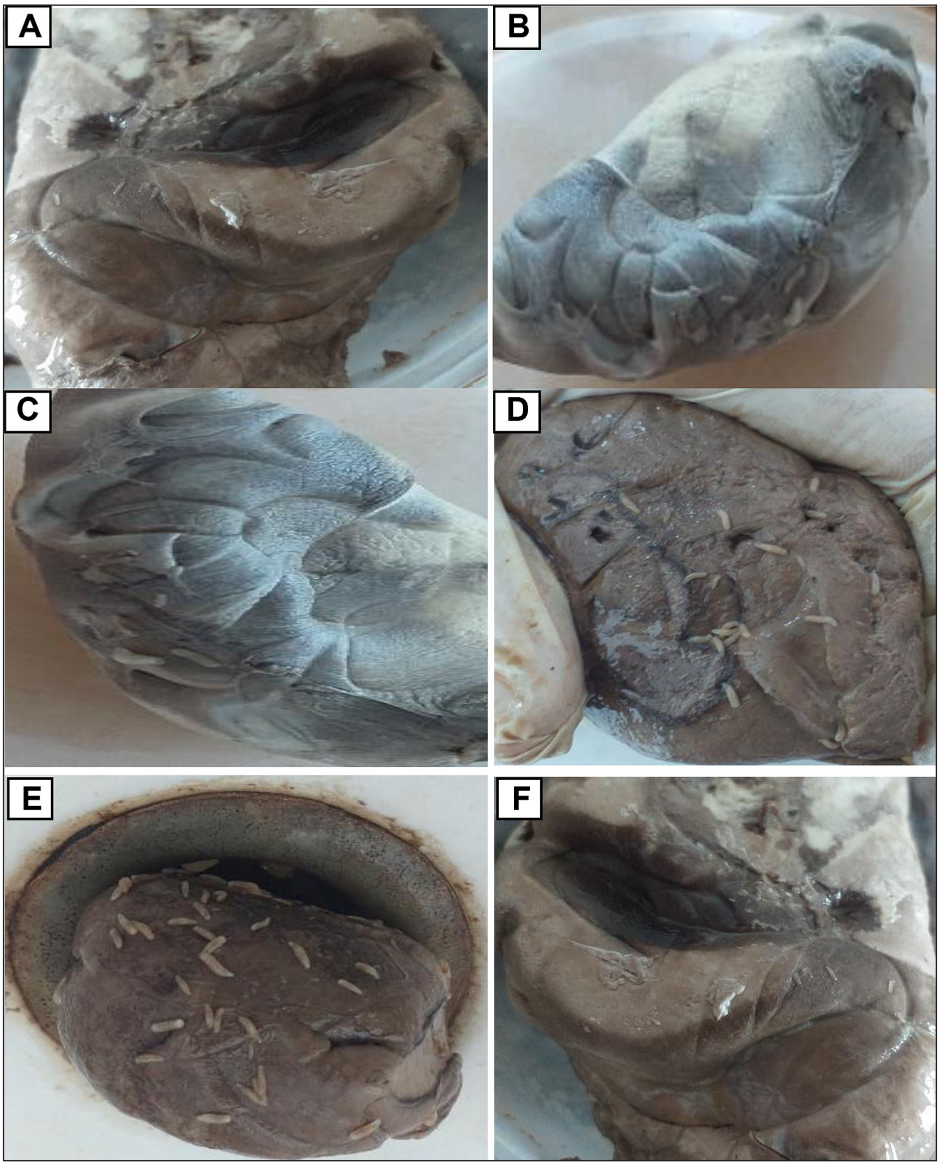

Figure 8. Larval growth on coagulated rubber samples with different liquid smoke treatments: (a) Latex without treatment (pure latex); (b) Latex treated with 10% grade 3 liquid smoke; (c) Latex treated with 10% non-grade liquid smoke; (d) Latex treated with 25% non-grade liquid smoke, showing increased larval activity; (e) Close-up of latex treated with 25% non-grade liquid smoke, highlighting significant larval infestation; (f) Latex without treatment for comparison

treated with higher concentrations of Grade III liquid smoke retained a lighter color and more compact structure, signifying improved preservation. As observed in Figures D and E, latex treated with 25% non-graded liquid smoke showed extensive microbial colonization, underscoring the limitations of non-graded liquid smoke at low concentrations (Desvita et al., 2021).

These findings highlight the dual functionality of liquid smoke as both a coagulant and preservative. At higher concentrations, particularly above 45%, Grade III liquid smoke effectively accelerates coagulation while providing antimicrobial protection, ensuring prolonged storage stability of the latex. Non-graded liquid smoke, while less effective due to its lower phenolic content and purity, still demonstrates potential for microbial inhibition when used at higher concentrations (Kailaku et al., 2017).

From a practical perspective, coal-derived liquid smoke offers several advantages over conventional chemical coagulants like acetic acid. In addition to facilitating rapid coagulation, liquid smoke extends the shelf life of latex by preventing microbial spoilage. This dual action makes liquid smoke an environmentally friendly and cost-effective alternative, particularly for smallholder farmers in rural areas where access to chemical coagulants may be limited. Further refinement of non-graded liquid smoke could enhance its performance, providing an affordable solution for latex producers (Brustolin et al., 2024). Thus, the results emphasize the importance of optimizing both the concentration and quality of liquid smoke to achieve superior coagulation performance and microbial resistance. High-quality Grade III liquid smoke, particularly at concentrations above 45%, demonstrated clear advantages in visual quality, microbial resistance, and overall latex preservation. Future research should focus on refining non-graded liquid smoke and exploring its scalability for wider industrial applications (Pilevar et al., 2017).

Analysis of dirt content, ash content, volatile matter and structure of latex

The results of dirt content, ash content, and volatile matter analyses for latex coagulated using liquid smoke (Grade III and non-graded) at various concentrations (10%, 25%, 45%, 50%, and 60%) are presented in Figure 9. The findings reveal that higher concentrations of liquid smoke significantly improved the quality of latex by reducing these parameters (Sinaga et al., 2023).

For dirt content, latex coagulated using Grade III liquid smoke at a 45% concentration achieved a value of 0.060%, which is well below the allowable maximum of 0.20% based on SNI 06-1903-2000 standards for standard indonesian rubber (SIR). Similarly, non-graded liquid smoke at the same concentration resulted in a dirt content of 0.068%, which also complies with the standard, though slightly higher than the Grade III result. In contrast, untreated latex exhibited a significantly higher dirt content of 0.22%, exceeding the standard limit. The reduction in dirt content demonstrates that liquid smoke effectively removes impurities during coagulation, with Grade III liquid smoke performing better due to its higher phenolic and acidic content, which promote the separation of contaminants (Gea et al., 2018).

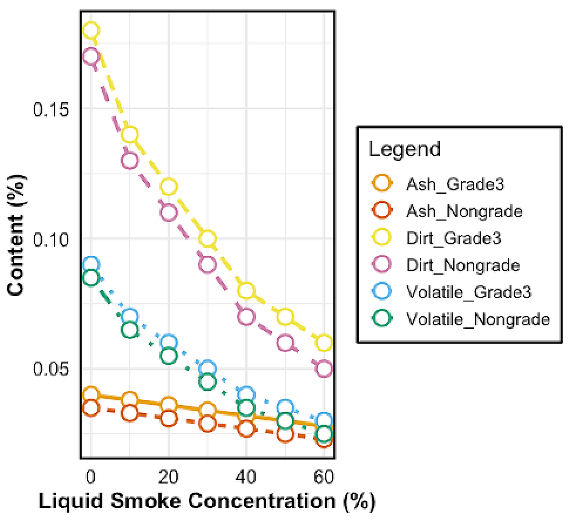

Figure 9. Content of latex vs liquid smoke concentration

The ash content of coagulated latex showed a similar trend. Latex treated with Grade III liquid smoke at a 45% concentration had the lowest ash content of 0.020%, while non-graded liquid smoke at the same concentration produced an ash content of 0.029%. Untreated latex, on the other hand, contained an ash content of 0.058%, reflecting the presence of more inorganic residues. A low ash content indicates high purity in the rubber, as ash is primarily composed of non-rubber substances such as minerals and impurities that can negatively affect the rubber's physical properties. These results highlight the role of acidic coagulants, such as liquid smoke, in facilitating impurity removal and achieving cleaner coagulated latex (Wibowo et al., 2016).

The volatile matter content in coagulated latex also decreased with increasing liquid smoke concentrations. Latex coagulated with Grade III liquid smoke at 10%, 25%, 45%, 50%, and 60% concentrations exhibited volatile matter contents of 0.037%, 0.033%, 0.025%, 0.020%, and 0.010%, respectively. In comparison, untreated latex had volatile matter values ranging from 0.065% to 0.014%, with the highest values occurring at lower coagulation levels. Volatile matter indicates the presence of moisture and organic compounds that can contribute to unpleasant odors, microbial activity, and poor rubber preservation. The lower volatile matter content observed in latex treated with Grade III liquid smoke suggests improved coagulation and reduced water retention, which enhance the quality and shelf life of the rubber (Evahelda et al., 2021).

Overall, the results indicate that Grade III liquid smoke at 45% concentration produced the best quality latex, with dirt content, ash content, and volatile matter values of 0.060%, 0.020%, and 0.025%, respectively. In comparison, non-graded liquid smoke at the same concentration resulted in slightly higher values of 0.068%, 0.029%, and 0.029%, while untreated latex exhibited the poorest performance with values of 0.22%, 0.058%, and 0.10%. The superior performance of Grade III liquid smoke can be attributed to its higher phenolic and acidic content, which enhances impurity removal and accelerates the coagulation process (Vachlepi, 2020).

In addition, the structural analysis of latex samples coagulated with Grade III liquid smoke and non-graded liquid smoke at a concentration of 45% was conducted using scanning electron microscopy (SEM) at a magnification of 500×(Figure 10). Latex samples without any coagulant were also included for comparison to evaluate the effect of liquid smoke on the microstructure of coagulated latex.

The SEM results, as shown in Figure 7a and 7b, revealed significant differences in the microstructure of the latex samples. Untreated latex (without a coagulant) displayed an irregular structure with numerous large voids and uneven particle distribution. These voids are indicative of incomplete coagulation, where significant amounts of water and impurities remain trapped within the rubber matrix, resulting in a porous and less compact structure. The poor quality of untreated latex can be attributed to the absence of acidic and phenolic compounds that facilitate particle aggregation during coagulation (Gea et al., 2018).

In contrast, latex coagulated using Grade III liquid smoke at 45% concentration exhibited a dense and uniform structure with minimal porosity. The compact and smooth arrangement of rubber particles reflects the effective coagulation achieved with Grade III liquid smoke. The higher concentration of acetic acid and phenolic compounds in Grade III liquid smoke plays a key role in destabilizing the colloidal latex particles, promoting the aggregation and formation of a tightly packed rubber matrix. This dense structure is associated with improved mechanical properties, such as tensile strength and elasticity, which are critical for high-quality rubber production (Sinaga et al., 2023).

Latex coagulated with non-graded liquid smoke at 45% concentration, however, showed a less uniform structure with smaller voids and slight irregularities compared to the Grade III-treated sample. The presence of residual impurities and lower concentrations of phenolic and acidic compounds in non-graded liquid smoke likely contributed to incomplete coagulation, resulting in a structure that was not as compact. Although non-graded liquid smoke demonstrated some efficacy as a coagulant, its performance was inferior to Grade III due to its lower chemical purity (Evahelda et al., 2021).

These microstructural differences align with the results of impurity analyses, which demonstrated lower dirt content, ash content, and volatile matter in latex coagulated with Grade III liquid smoke. Figure 11 showed the comparison of this study and other previous study. These values further highlight the superior quality of latex treated with Grade III liquid smoke, as the removal of impurities allows for a denser and cleaner rubber matrix (Wibowo et al., 2016).

The improved structure observed in latex coagulated with Grade III liquid smoke can be attributed to its chemical composition, particularly its higher concentrations of acetic acid and phenolic compounds. Phenolic compounds act as natural coagulants and antimicrobial agents, facilitating particle aggregation while preventing microbial spoilage. The purification process of Grade III liquid smoke, which includes the removal of

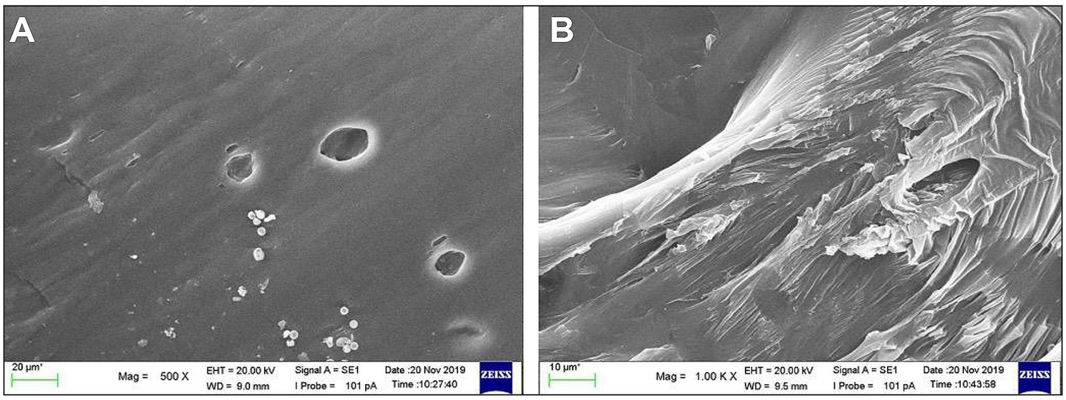

Figure 10. SEM analysis of latex with 45% Grade III liquid smoke (a) and latex with 45% non-grade III liquid smoke (b) at 500× magnification

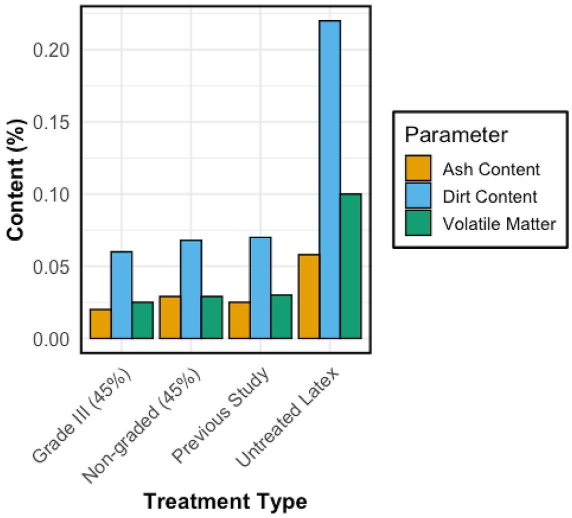

Figure 11. Comparison of liquid smoke

non-volatile residues, further enhances its efficacy as a coagulant (Triawan et al., 2022).

The quality of liquid smoke is closely related to its pH, acidity, and phenolic content, as observed in the compositional analysis. Purified liquid smoke, particularly when treated with active bentonite, exhibited a pH of 2.06, acidity of 13.60%, and phenolic content of 11.67 mg GAE/100 g. These values demonstrate the correlation between high acidity, phenolic content, and improved coagulation performance. A lower pH facilitates faster coagulation, while higher phenolic content enhances the removal of impurities and improves the structural integrity of the rubber matrix (Nugroho et al., 2019).

Furthermore, the structural integrity of coagulated latex directly impacts its mechanical properties. A dense and uniform structure, as observed in Grade III-treated latex, ensures better tensile strength, elasticity, and durability, which are critical for industrial applications. Conversely, the porous structure observed in untreated latex and non-graded liquid smoke-treated latex can lead to weaker rubber, as the voids act as stress concentration points that make the material more prone to tearing under tension (Lilis Rosmainar et al., 2020).

Thus, the SEM analysis highlights the significant influence of liquid smoke quality and concentration on the microstructure of coagulated latex. Grade III liquid smoke at 45% concentration produced the most compact and uniform structure, reflecting its superior ability to remove impurities and facilitate efficient coagulation. Non-graded liquid smoke, while effective, resulted in a less uniform structure due to its lower chemical purity. Untreated latex, with its highly porous structure, demonstrated the poorest quality, emphasizing the importance of using effective coagulants for high-quality rubber production. These findings further support the use of purified liquid smoke, particularly Grade III, as an optimal and sustainable coagulant for latex processing.

Field application

The field application of coal-derived liquid smoke for latex coagulation was conducted with the Mekar Sari Farmers Group in Ladang Panjang Village, Sungai Gelam Subdistrict, Muaro Jambi Regency, during October 2024. Ladang Panjang Village is located approximately 120 kilometers from Universitas Jambi, requiring a 3-hour journey by road. The activity began with a field survey to observe the rubber plantations and to socialize the research objectives with the farmers. Researchers, including lecturers and students, directly observed the rubber tapping process, the collection and transportation of latex to middlemen (tengkulak), and performed coagulation trials using liquid smoke at the collection site. In addition, interviews were conducted with farmers to gather insights about latex yields, farming challenges, and economic constraints. The location of Ladang Panjang Village and its latex collection site is shown in Figure 12.

Rubber tapping in the village is typically performed once a week or every 15 days, depending on weather conditions and the health of the rubber trees. Tapping is done during clear weather in the early morning between 6:00 AM and 10:00 AM. Rainy conditions often prevent tapping because rainwater contaminates the latex, causing it to overflow from collection cups or wash away. Once the tapping process is complete, latex collection starts around 11:00 AM and continues until 1:00 PM. The collected latex is then transported to middlemen, where coagulation processes are traditionally performed. During this study, liquid smoke was introduced as an alternative coagulant to conventional chemical coagulants such as formic acid (Gentong brand) or sulfuric acid.

The use of liquid smoke demonstrated several advantages over traditional coagulants. Farmers noted that latex coagulated quickly, producing a firm and stable structure. The resulting rubber had a low moisture content, measured to be below 45%, which is essential for improving rubber quality and market value. Additionally, the rubber

Figure 12. Ladang Panjang Village

produced using liquid smoke was free from foul odors and microbial spoilage, even after prolonged storage. This result can be attributed to the phenolic compounds and acidity of liquid smoke, which inhibit bacterial growth and preserve the latex. Farmers observed that the rubber produced with liquid smoke did not develop maggots or decay, unlike rubber treated with lower-quality coagulants or stored untreated. This improved quality resulted in a higher selling price, providing economic benefits for farmers (Evahelda et al., 2021).

The Mekar Sari Farmers Group consists of 20 members, each owning a minimum of 2 hectares of rubber plantations. On average, the group produces 1.5 tons of latex per month per farmer, resulting in a total collection of approximately 30 tons of latex per month at the middlemen's site. The quality of rubber produced by the group is highly influenced by moisture content and cleanliness. For comparison, latex processed using conventional chemical coagulants often has a moisture content above 45%, with some cases exceeding 50%, reducing its market value. This issue is mitigated through the use of liquid smoke, which produces drier rubber with improved visual and structural quality. Figure 13 illustrate the rubber tapping, collection, and coagulation process using liquid smoke.

While the introduction of liquid smoke has shown promising results, farmers continue to face significant challenges. One of the most pressing issues is the decline in latex yields caused by unstable weather and climate conditions. Frequent rainfall disrupts tapping schedules, while prolonged dry periods reduce the productivity of rubber trees. Additionally, rubber trees in the village suffer from leaf shedding and the yellowing of foliage, which significantly impact latex production. If young leaves fail to regrow, latex yields decline sharply. Another critical challenge is the

Figure 13. Collecting the latex (a-b), application of latex with liquid smoke (c-e), product of latex after added liquid smoke (f-h)

presence of white root fungal disease, which attacks the roots of rubber trees, weakening their health and eventually causing tree mortality. These conditions, exacerbated by inconsistent climate patterns, have led to a notable reduction in latex production across the village (Nugroho et al., 2019).

Farmers also face economic constraints due to their reliance on middlemen (tengkulak) to sell their latex. Although some farmers produce high-quality rubber, they are often paid the same price as those producing lower-quality rubber, as middlemen do not always differentiate based on quality. This system limits farmers' bargaining power and financial returns, preventing them from fully benefiting from their labor and resources. Consequently, many farmers have opted to convert their rubber plantations into oil palm plantations, which are perceived to offer higher and more stable economic returns.

The successful implementation of liquid smoke as a coagulant in Ladang Panjang Village highlights its potential as an affordable and sustainable alternative to chemical coagulants. The ability of liquid smoke to improve rubber quality, reduce moisture content, and extend storage stability without spoilage provides significant economic advantages. However, to maximize the benefits of this technology, it is essential to address the broader challenges faced by rubber farmers. Efforts should focus on improving disease management strategies, promoting climate-resilient farming practices, and establishing cooperative marketing systems to enable direct sales to factories. These steps can enhance farmers' profitability and sustainability, reducing the trend of land conversion to oil palm plantations (Gea et al., 2018).

The field application demonstrated that coal-derived liquid smoke offers a practical solution for improving latex coagulation and rubber quality in rural communities. By addressing both technical and economic challenges, this approach has the potential to support smallholder farmers, strengthen rural economies, and promote sustainable rubber production in regions like Ladang Panjang Village.

Environmental concern regarding liquid smoke utilization

Asd The production of coal-derived liquid smoke involves pyrolysis, a thermal process that generates gaseous emissions, including carbon dioxide (CO_2), carbon monoxide (CO), sulfur oxides (SO_x), and nitrogen oxides (NO_x). These emissions can contribute to air pollution and greenhouse gas accumulation if not managed effectively. For instance, pyrolysis of coal liquefaction residue can yield up to 34.81% oil at 540 °C, and the introduction of green hydrogen and oxygen has been shown to reduce CO_2 emissions to near-zero levels (Tian et al., 2022). To mitigate these environmental impacts, emission capture systems such as scrubbers or filtration technologies can be installed in the pyrolysis reactor to neutralize harmful gases. Additionally, optimizing the operating conditions of reactors, such as maintaining precise temperatures and minimizing secondary reactions, can help reduce incomplete combustion and lower emission levels. Quantitative analysis of emission profiles indicates that co-pyrolysis can reduce annual CO_2 emissions by 1,720 tons and significantly lower SO_2 and smoke emissions (Yao et al., 2021). These findings provide insights into the environmental performance of coal-derived liquid smoke compared to biomass-based alternatives.

Two significant byproducts of the pyrolysis process are tar and char, both of which pose potential environmental risks if not properly managed. Tar, a viscous organic compound, can leach hazardous substances into soil and water, leading to contamination. However, it also holds potential as an industrial feedstock, particularly as an additive in road construction or as a precursor for chemical synthesis. Similarly, char, composed primarily of carbon, can be repurposed for beneficial uses, such as a soil amendment to enhance fertility and sequester carbon, or as an adsorbent material for wastewater treatment, particularly for heavy metal removal. Activated coke-based fluidized bed reactors have been shown to degrade phenolic compounds in wastewater with an efficiency of 90%, significantly higher than traditional activated sludge reactors (Zheng et al., 2021). By focusing on the reuse of these byproducts, the environmental footprint of the pyrolysis process can be minimized, aligning with circular economy principles that prioritize turning waste into valuable resources.

While coal-derived liquid smoke offers consistent composition and scalability, it may have a larger environmental footprint than biomass-derived alternatives. Coal pyrolysis typically results in higher emissions and requires greater energy input compared to biomass pyrolysis. For example, adding iron during coal pyrolysis has been shown to reduce soot formation by 48–68% while altering the graphite structure in soot, thereby improving environmental outcomes (Li et al., 2020). However, coal's advantage lies in utilizing an abundant and often underutilized resource, such as low-grade coal, that might otherwise remain unused. A comprehensive lifecycle analysis comparing the environmental impacts of coal- and biomass-derived liquid smoke could provide valuable insights to guide future development and optimize sustainability.

In latex coagulation, coal-derived liquid smoke offers several environmental benefits. By replacing conventional chemical coagulants such as acetic acid and formic acid, it eliminates the environmental hazards associated with the production, transportation, and disposal of these chemicals. Additionally, the phenolic and acidic compounds present in liquid smoke enhance its antimicrobial properties, reducing spoilage and extending the shelf life of coagulated latex. This dual function eliminates the need for additional preservatives, further lowering environmental impacts. Moreover, the localized production and application of liquid smoke using regional coal resources reduce transportation emissions and bolster rural economic sustainability.

Despite these advantages, challenges remain. The pyrolysis process for producing coal-derived liquid smoke is energy-intensive, which can increase carbon emissions unless renewable energy sources are integrated into production. For example, pressurized oxy-fuel pyrolysis experiments demonstrated that sulfur concentrations in emissions could be significantly reduced with increased operating pressure, highlighting a pathway to better sulfur management (Li et al., 2020). Furthermore, the purification process generates wastewater that may contain acidic or phenolic residues, which must be treated to prevent environmental contamination. As production scales up, continuous monitoring and implementation of best practices are essential to ensure environmental impacts remain within acceptable limits.

Overall, the development and utilization of coal-derived liquid smoke support global sustainability objectives by promoting resource efficiency and cleaner production in the rubber industry. This technology provides an eco-friendly alternative to traditional coagulants, contributing to the reduction of industrial emissions and supporting the adoption of sustainable practices. By addressing the challenges of emissions, byproduct management, and energy efficiency, coal-derived liquid smoke can play a significant role in advancing environmental sustainability in rural and industrial applications.

Limitation and future research direction

This study highlights the potential of coal-derived liquid smoke as an environmentally friendly coagulant for latex production; however, several limitations require consideration. Firstly, the environmental assessment of the pyrolysis process primarily focused on qualitative descriptions of emissions and byproducts, without detailed quantitative measurements. The lack of precise data on gaseous emissions, such as carbon dioxide (CO_2), sulfur oxides (SO_x), and nitrogen oxides (NO_x), limits the comprehensive evaluation of the ecological footprint associated with coal-derived liquid smoke production. Such data is critical for a robust understanding of its environmental sustainability. Supporting evidence shows that the absence of systematic and quantitative assessments of gaseous emissions in similar coal-derived processes has been identified as a significant research gap (Hertianti et al., 2023).

Additionally, while the study demonstrates the effectiveness of coal-derived liquid smoke in latex coagulation, the broader environmental implications of its application have not been fully explored. Potential risks such as soil or water contamination from residual compounds in the coagulated latex remain unexamined. Furthermore, the long-term effects of using coal-derived liquid smoke on the mechanical properties, durability, and market competitiveness of rubber products are yet to be investigated. These gaps hinder the complete evaluation of this material's industrial viability and environmental compatibility. Research has indicated that liquid smoke derived from other materials, such as plant biomass, can enhance rubber quality while reducing environmental impacts, but these findings need broader validation (Hertianti et al., 2023).

The scope of field trials conducted in this study was geographically limited to a single region and involved a relatively small group of farmers. While these trials yielded promising results, they may not adequately represent the scalability and adaptability of this technology under diverse environmental conditions, varying coal types, and differing latex production practices.

This limitation underscores the need for broader and more diverse field studies to validate the findings. Comparative studies with other liquid smoke sources, such as rubber wood or sawdust-derived liquid smoke, demonstrate the importance of geographic and raw material diversity in assessing scalability (Triawan et al., 2022).

To address these limitations, future research should focus on several critical areas. First, a comprehensive lifecycle assessment (LCA) of coal-derived liquid smoke production and application is necessary. This should include precise quantification of gaseous emissions, energy consumption, and byproduct management. Comparative studies with biomass-derived liquid smoke and conventional chemical coagulants would further elucidate its environmental performance and sustainability. Studies have shown that integrating renewable energy into pyrolysis systems can significantly reduce emissions and improve sustainability metrics (Winarni et al., 2021).

Another key area of research is the valorization of byproducts, such as tar and char, generated during the pyrolysis process. Tar could be repurposed as an additive in road construction or as a precursor for industrial chemicals, while char, with its high carbon content, holds promise as a soil amendment for carbon sequestration or as an adsorbent for wastewater treatment. Converting these byproducts into valuable resources would not only minimize environmental impact but also enhance the economic feasibility of coal-derived liquid smoke production. Evidence suggests that high-carbon byproducts from pyrolysis have been successfully utilized in agriculture and environmental applications, further supporting their potential for value addition (Sinaga et al., 2023).

Long-term performance evaluations are also essential to establish the suitability of coal-derived liquid smoke for industrial applications. Future studies should investigate its impact on the mechanical properties and durability of rubber products, as well as the potential leaching of residual compounds. Understanding its compatibility with various grades of latex will further support its widespread adoption. Research on similar coagulants has shown that detailed assessments of product quality over extended periods are critical for industrial acceptance (Keeley et al., 2014).

Expanding field trials to include diverse regions with varying climatic, economic, and agricultural conditions is critical to assess the scalability and adaptability of this technology. Collaborations with farmers, cooperatives, and industries will provide valuable insights into the economic and practical feasibility of implementing coal-derived liquid smoke on a larger scale. Optimizing the pyrolysis process to enhance energy efficiency and integrating renewable energy sources into production systems are other important research directions. Improvements in reactor design and process modifications could significantly reduce energy consumption, thereby increasing the environmental sustainability of coal-derived liquid smoke. Studies of pyrolysis processes at different scales have highlighted the importance of design improvements for efficiency and sustainability (Adiningsih et al., 2021).

Finally, establishing international standards for coal-derived liquid smoke, including benchmarks for phenolic and acidic content, will facilitate its acceptance in global markets. Refining production and purification methods to consistently meet these standards is essential for promoting its industrial application and market integration. Addressing these research gaps will enhance the understanding and application of coal-derived liquid smoke, positioning it as a sustainable, scalable, and environmentally responsible alternative in the latex and rubber industries. These advancements will not only improve its practical utility but also contribute to global efforts to reduce the environmental footprint of industrial processes and promote sustainable development.

CONCLUSIONS

Coal demonstrates significant potential as a versatile raw material for producing high-value products such as liquid smoke and activated carbon using advanced 3-in-1 pyrolysis reactor technology. This study has confirmed that coal-derived liquid smoke is highly effective for natural latex coagulation, with its quality evaluated based on critical parameters including pH, phenol content, and acetic acid concentration. The optimal performance of Grade III coal-derived liquid smoke was observed at concentrations above 40%, where rapid coagulation occurred within 5–7 minutes, resulting in high-quality rubber that met national standards (SNI). Key metrics, including impurity levels (<0.200%), ash content (<1%), and volatile matter (<0.80%), highlight its capability to produce premium rubber. Despite these promising results, the pH of the liquid smoke produced in this study (4.09) falls short of international quality standards, such as those set by Japan. This underscores the need for further refinement and purification processes to elevate its quality to meet global benchmarks. Addressing this challenge will enhance the material's utility in industrial applications and expand its potential marketability.

The successful implementation of coal-derived liquid smoke in field trials with the Mekar Sari Farmers Group in Ladang Panjang Village, Muaro Jambi Regency, demonstrated its practicality and economic benefits. Farmers noted accelerated coagulation, improved rubber quality, and the elimination of unpleasant odors and microbial spoilage, which collectively increased the market value of the latex. These outcomes highlight the dual benefits of coal-derived liquid smoke: improving product quality while promoting sustainability in rubber production. Moving forward, refining production technologies to achieve internationally standardized liquid smoke quality is essential. Additionally, broader industrial applications should be explored to maximize its value. This includes leveraging the byproducts of the pyrolysis process, such as tar and char, for complementary uses in other industries. Such developments will not only advance the environmental and economic sustainability of the rubber industry but also position coal-derived liquid smoke as a pivotal innovation in global industrial practices. Thus, the utilization of coal as a raw material for liquid smoke production offers a sustainable, cost-effective solution that aligns with national and global objectives for cleaner production and economic growth. By addressing current limitations and scaling its application, coal-derived liquid smoke can significantly contribute to enhancing the quality and competitiveness of natural latex while supporting sustainable development in the rubber industry.

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