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Wood Vinegar Applications: Quality, Efficacy, and Commercial Prospects for SMEs

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ABSTRACT

Wood vinegar, scientifically defined as the condensation product of thermal decomposition (pyrolysis) of biomass rich in cellulose, hemicellulose, and lignin, presents a critical strategic step in efficient biomass waste management in Indonesia. Raw materials like coconut shells and palm oil waste are abundant, making their market potential highly promising. However, Indonesian Small and Medium Enterprises (SMEs) predominantly produce Grade 3 wood vinegar, which contains high levels of carcinogenic tar, hindering access to premium food-grade and pharmaceutical markets. This review aims to present a comprehensive report on the scientific characteristics and quality classification of wood vinegar, specifically analyzing the mechanism of action, effectiveness, and potential use of Grade 3 as an anti-termite agent (termiticide) and wood preservative, alongside its other advanced applications, such as food preservation, agricultural biopesticide, and latex coagulant. The method employed is a literature review, synthesizing data on chemical composition, purification standards (SNI and BPOM), and experimental findings on its multi-functional properties. The main conclusion is that Grade 3 wood vinegar proves highly effective as a termiticide, providing total wood protection and offering a safe, sustainable alternative to chemical wood preservatives. For food applications, rigorous purification to Grade 1 is essential to replace harmful practices like using formalin or borax. The novelty of this study lies in its integrated analysis of the technical efficacy (Grade 3 in termiticide) and the regulatory/commercial trade-off with food safety requirements (Grade 1), culminating in strategic recommendations for developing downstream purification technology for Indonesian SMEs

Keywords: *Wood Vinegar, Pyrolysis, Termiticide, Coagulant, Pesticide.*

1. INTRODUCTION

Wood vinegar is scientifically defined as the condensation result of vapors released through the thermal decomposition process, known as pyrolysis [1], [2], [3]. This process utilizes biomass raw materials rich in organic structural components, namely cellulose, hemicellulose, and lignin [4]. In Indonesia, raw materials for wood vinegar production are abundant, often consisting of agricultural and plantation waste, including coconut shells, rice husks, rubber fruit shells (*Hevea braziliensis*), and empty palm oil fruit bunch waste [5], [6], [7].

The development of pyrolysis technology is a critical strategic step in efficient biomass waste management, transforming residual materials previously considered valueless into high-value-added products [8], [9]. The utilization of this waste supports environmental sustainability while offering significant economic potential [10], [11]. Global and domestic market potential is highly promising, supported by Indonesia's status as the world's largest coconut producer, which guarantees a stable supply of raw materials.

The adoption of wood vinegar offers significant operational and health advantages compared to traditional smoking methods[12], [13]. Operationally, the use of wood vinegar allows for a faster and easier application process [14]. Furthermore, wood vinegar provides final product characteristics such as aroma, color, and taste that tend to be more standardized [15].

From an environmental and health perspective, wood vinegar is far superior. Its use does not pollute the environment. Most importantly, purified wood vinegar (Grade 1) substantially reduces the risk of direct exposure to carcinogenic compounds such as tar, which are often abundant in direct smoking methods or in non-purified wood vinegar [16], [17]. Therefore, purified wood vinegar is a solution to increase food shelf life while reducing health hazards, in contrast to harmful chemical preservation practices.

This review aims to present a comprehensive report on the scientific characteristics of biomass wood vinegar, from its chemical composition to its quality classification system. The report specifically analyzes the effectiveness, mechanism of action, and potential use of Grade 3 as a termiticide and wood preservative. In addition, important non-termiticide applications will be reviewed, such as food preservation, its role as an agricultural biopesticide, industrial latex coagulant, and an in-depth analysis of the commercial prospects and regulatory challenges for SMEs (Small and Medium Enterprises) in Indonesia.

2. LITERATURE REVIEW

Scientific Characterization, Chemical Composition, And Quality Classification

2.1 Pyrolysis Process and Functional Components

The chemical composition of wood vinegar is highly complex and dominated by functional compounds resulting from the thermal decomposition of structural biomass components [18], [19]. Key compounds include organic acids, derived from hemicellulose; phenol compounds, derived from lignin; and carbonyl compounds [9], [10], [20]. These compounds give wood vinegar its diverse functional properties, such as antibacterial activity and acidic nature [3], [18].

Chemical analysis using gas chromatography–mass spectrometry (GC-MS) has confirmed the dominance of certain compound groups [21]. For instance, studies indicate that Grade 3 wood vinegar contains Acetic Acid and Phenol as the dominant components [22], [23]. These high concentration levels of Acetic Acid and Phenol are key to wood vinegar's effectiveness in technical applications, particularly as a disinfectant and preservative agent [24], [25].

2.2 Quality Grading System and Application Requirements

The quality classification of wood vinegar in Indonesia is based on the level of purification, which directly correlates with the removal of carcinogenic tar. The higher the grade, the lower the content of harmful substances, making it safer for use in food materials. Its physical quality and applications can be summarized in the following table 1.

Table 1. Wood vinegar Quality Classification Based on Usage Standards

Quality Grade	Key Physical Characteristics	Primary Application	Tar Content and Purification Requirements	Relevant Sources
Grade 1 (Premium Food Grade)	Clear color, Slightly acidic taste, Neutral aroma	Food preservative and flavoring,	Very low tar. Requires intensive purification (distillation,	[4], [9], [26], [27], [28]

		Pharmaceutical, Cosmetics	zeolite/active carbon filtration)	
Grade 2 (Semi-Food Grade)	Transparent brownish color, Moderately acidic taste, Weak smoke aroma	Foods with smoky taste (smoked meat, meatballs, dried fish)	Moderate tar. Higher than Grade 1, but below certain tolerance limits.	[4], [26], [29], [30]
Grade 3 (Industrial/Technical Grade)	Reddish brown, Very pungent odor, Black sediment (Tar)	Biopesticide, Latex Coagulant, Anti-termite wood preservative, Disinfectant	High tar. Still contains much carcinogenic tar. Not safe for food.	[11], [24], [31], [32], [33], [34], [35], [36]

The fundamental difference in this classification creates a trade-off situation between active ingredient efficacy and food safety. Grade 3 has a very high concentration of acids and phenols, providing optimal lethality for industrial or pesticide applications [5]. However, the high tar content accompanying this grade makes it unsafe for consumption [37]. Therefore, the purification process to achieve Grade 1 must be designed to balance the maximal removal of carcinogenic tar while retaining the functional compounds that provide preservative properties and a neutral aroma.

2.3 *Standardization and Quality Regulation in Indonesia*

To ensure quality and safety, wood vinegar products must comply with established technical standards. Wood vinegar quality is tested based on SNI No. 8985:2021, which includes parameters such as color, specific gravity, pH, and acetic acid content.1 Compliance with SNI is a prerequisite for ensuring quality, including the quality of derivative products, as seen in the processed rubber standard SNI-06-1903-2000.

Food safety issues are strictly regulated by BPOM (National Agency of Drug and Food Control). For producers wishing to supply the food sector, wood vinegar must undergo purification to achieve tar-free Grade 1 [38]. The biggest implementation challenge lies at the SME level, which often still produces Grade 3 [35]. Investment in in-depth purification technique training (distillation) and equipment standardization is key to enabling SMEs to access food-grade and pharmaceutical markets.

3. METHODS

Exclusive Focus: Wood Vinegar As An Anti-Termite Agent (Termiticide)

3.1 Standardization and Quality Regulation in Indonesia

Subterranean termites (*Coptotermes curvignathus*) are among the most detrimental wood-destroying pests [39], [40]. Although synthetic chemical preservatives have long been used, the environmental and health problems they cause encourage the search for sustainable natural alternatives [41], [42]. Grade 3 wood vinegar emerges as a superior candidate due to its high content of naturally toxic chemical compounds [31], [32], [33], [43].

3.2 Mechanism of Toxicity and Anti-Fungal Action

The effectiveness of Grade 3 wood vinegar as a termiticide lies in its phenol and acetic acid content [7], [9], [21]. Phenol compounds function as disinfectants, while acetic acid acts as an anti-fungal and antibacterial agent [24], [44], [45].

The mechanism of phenol toxicity in termites is multiple and invasive. This compound works by disrupting cell membrane permeability, inactivating essential enzymes, and damaging genetic material, which on finally leading to cellular dysfunction and death [31], [32], [46]. Acetic acid supports this by inhibiting the growth of wood-destroying microorganisms that can weaken the material, and is suspected to directly acidify the termite's cytoplasm [42], [47]. This high efficacy is a direct result of the adequate concentration of phenolic compounds in Grade 3 to penetrate and massively damage the biological structure of the termites [48], [49].

3.3 Mechanism of Toxicity and Anti-Fungal Action

Research on subterranean termites shows a very clear dose-response relationship: increasing the concentration of wood vinegar significantly increases mortality and lowers the rate of wood weight loss [31], [32], [46]. Experimental data using palm oil trunk wood vinegar as a preservative for pulai wood against subterranean termites *C. curvignathus* yielded very convincing findings [45]:

4. RESULT AND DISSCUSION

Advanced Application I: Natural Food Preservation Solution

4.1 Mechanism of Toxicity and Anti-Fungal Action

Formalin and borax are still often misused in the fast-food industry to extend product shelf life, even though the use of these chemicals in excessive amounts has been proven to cause serious negative effects on human health [50], [51]. Purified wood vinegar (Grade 1) becomes a safe natural preservative solution [4], [25]. The phenolic and acidic compounds in wood vinegar function as antibacterial and antioxidant agents, which effectively inhibit food-destroying microorganisms, thereby increasing shelf life without posing health risks like formalin [26], [29].

4.2 Dual Mechanism of Food Preservation

Wood vinegar preserves food through a combination of chemical and physical effects. Chemically, acid and phenol compounds act directly as antimicrobial and antioxidant agents, slowing down the microbiological degradation process [25], [30]. Physically, research on beef shows that soaking using wood vinegar can reduce the water content in beef. Low water content is an essential inhibitor of microorganism development, as water availability is an ideal substrate for the growth of spoilage bacteria [28], [52]. This dual effect results in a significant extension of shelf life.

4.3 Specific Applications Studies on Food

The application of wood vinegar as a preservative has been tested on various products. In fishery products, wood vinegar from galam wood in the form of a biodegradable film successfully maintained the microbiological quality of snakehead fish, characterized by a decrease in TPC and coliform [53]. Wood vinegar is also capable of preserving fish with a shelf life of between 14 days [54]. Meanwhile, for beef, a 1.5% concentration of coconut shell wood vinegar can extend shelf life up to 3 days at room temperature[53].

Because safety is the priority, wood vinegar used in food must undergo strict purification (distillation, active zeolite filtration, and active carbon filtration) to achieve food-grade quality. The optimal concentration for food (1.5% for beef) is much lower than for anti-termite applications, highlighting that Grade 1 purification must produce a product with measurable active ingredient concentration, prioritizing safety and neutral aroma over total lethality

Advanced Application II: Biopesticide and Rubber Industry Coagulant

4.4 Wood vinegar as an Agricultural Biopesticide

Beyond its role as a termiticide, Grade 3 wood vinegar also functions broadly as an agricultural biopesticide and insecticide. Research has proven its effectiveness against key pests, including brown planthopper (*Nilaparvata lugens*) and white thrips (*Thrips Tabaci*) [55].

In one study, a 3% wood vinegar application on brown planthopper showed an average insect mortality rate of 82.5% [56]. This result was statistically not significantly different compared to the application of chemical insecticide with chlorpyrifos as the active ingredient, confirming the potential of wood vinegar as an effective natural substitute for conventional agricultural chemicals [14].

4.5 Specific Applications Studies on Food

Research using coal wood vinegar as a coagulant, tested for quality using the SNI-06-1903-2000 method, shows that the optimal wood vinegar concentration for latex coagulation is 45%.

Increasing the wood vinegar concentration up to 45% consistently improves the quality of crumb rubber, characterized by a decrease in impurity content, ash content, and volatile matter content [57]. The research also highlights the importance of the preservation function in the coagulation process; concentrations that are too low (such as 10% Grade 3 or 10% and 25% non-grade) fail to inhibit bacterial growth, causing the coagulum to be infested with maggots within 5 days. This multifunctional property (coagulation and preservation) ensures the rubber product meets SNI standards and increases market competitiveness.

Furthermore, the antibacterial potential of wood vinegar has also been proven in the health sector [33], [34], [58]. Wood vinegar at concentrations of 12.5%, 25%, and 50% is effective for use as a disinfectant for dental clinic instruments, with comparable effectiveness to 70% alcohol.

Commercial Prospects, Sme Challenges, And Strategic Recommendations

4.6 Analysis of Indonesia's Raw Material Potential

The prospects for the wood vinegar industry in Indonesia are very bright, supported by the massive availability of biomass waste raw materials. Indonesia produces around 58.37% global export of coconut [59], with coconut shells accounting for about 15% of that total. The availability of this waste (including rice husks and palm oil waste) ensures a continuous supply of raw materials for the pyrolysis process.

Market potential is not limited to Grade 3 for agro-industry, but extends to premium Grade 1 highly needed by the global cosmetics, pharmaceutical, and *food grade* industries.

4.7 Quality, Marketing, and Legality Challenges for SMEs

Although natural resources are abundant, SME actors face structural challenges that hinder growth. The main problem is non-uniform product quality, where most SMEs still produce Grade 3 that does not meet Grade 1 standards [5]. Training and mentoring on purification techniques (such as distillation) are needed to improve quality and enable product diversification [60].

Distribution and legality barriers are also significant. Marketing challenges often arise due to simple product packaging and limited business legality. Furthermore, government assistance in the form of equipment is often not aligned with the actual needs of SMEs, which hinders the process of improving production quality [61]. The availability of raw materials cannot be translated into competitive advantage without quality improvement and regulatory compliance. Investment in in-depth purification technique training is key to unlocking the economic potential of the premium market.

4.8 Research Directions and Strategic Recommendations

Future research directions need to focus on developing specific formulations, especially for broad-spectrum biopesticide and health disinfectant applications, leveraging the findings of high antibacterial activity.

Strategically, coordinated regulatory and technological intervention is needed. The main recommendation is to encourage downstream purification technology programs for SMEs, which include the standardization of pyrolysis and distillation equipment. The government must strengthen the implementation of SNI and BPOM at the SME level through simplified certification and legal assistance, facilitating the transition from Grade 3 to Grade 1. Furthermore, the utilization of web-based marketing strategies should be encouraged to expand market reach, overcoming distribution limitations faced by SMEs

CONCLUSION

Biomass wood vinegar is a superior pyrolysis product with phenol and acetic acid content, making it a multifunctional agent. In termiticide applications, Grade 3 wood vinegar proves highly effective, providing total wood protection. This offers a safe and sustainable alternative to chemical wood preservatives. In the food sector, after strict purification to Grade 1, wood vinegar functions as a safe natural preservative, potentially replacing formalin and borax. In the rubber industry, the use of 45% wood vinegar as a coagulant is proven optimal in improving quality according to SNI standards, while also addressing bacterial damage and low-quality issues.

Industrialization efforts should focus on advancing purification technology in downstream SME programs to boost the competitiveness of Indonesian products in global premium markets such as pharmaceuticals, cosmetics, and food-grade products, by utilizing abundant local raw materials. These initiatives must be supported by regulatory harmonization through simplified SNI and BPOM certification and structured legal assistance to address marketing and distribution barriers. In addition, applied research should prioritize developing new formulations for broad-spectrum biopesticides and health disinfectants, leveraging proven antibacterial potential for diversification beyond the agro-industrial sector.

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