



REVIEW ARTICLE

Coconut Shell Liquid Smoke (CSLS) as a Sustainable, Natural Preservative in Fisheries: A Comprehensive Review on Thermochemical Processes, Efficacy, Safety and Future Prospects

Haniif Prasetiawan^{1,*}, Dewi Selvia Fardhyanti¹, Hanif Ardhiyansyah¹, Fisa Savanti², Bayu Triwibowo¹

¹*Chemical Engineering Department, Faculty of Engineering, Universitas Negeri Semarang, UNNES Kampus Sekaran, Gunungpati, Semarang 50229 Indonesia*

²*Architecture Engineering Department, Faculty of Engineering, Universitas Negeri Semarang, UNNES Kampus Sekaran, Gunungpati, Semarang 50229 Indonesia*

(*Corresponding author's e-mail: haniif.prasetiawan@mail.unnes.ac.id)

Received: 20 August 2026, Revised: 22 September 2026, Accepted: 23 September 2026, Published: 25 September 2026

Abstract

This review article synthesizes findings from the last two decades (2010–2026) on the preparation, chemical composition, preservation efficacy, and safety profile of coconut shell liquid smoke (CSLS) as a natural, sustainable fish preservative. Conventional slow pyrolysis (yielding optimal phenol levels at 450–550°C) and advanced Microwave-Assisted Pyrolysis (MAP, achieving yields up to 34.6% and operating at 255–280°C with 2–3 mm particle sizes) represent the primary thermochemical techniques. Purification via redistillation, filtration, and membrane separation (ultrafiltration/nanofiltration) successfully minimizes toxic polycyclic aromatic hydrocarbons (PAHs), producing food-grade liquid smoke (grades A and B) that complies with strict safety standards. CSLS contains key phenolic compounds, organic acids, and carbonyls that provide dual antimicrobial and antioxidant actions. Minimum Inhibitory Concentrations (MIC) of 0.22% to 0.40% are effective against major spoilage pathogens such as *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Escherichia coli*. Applications of CSLS at concentrations of 2.5% to 7.0% significantly extend the shelf life of various fish products (fillets, balls, cakes). Advanced delivery formulations, including edible chitosan coatings and chitosan/maltodextrin nanocapsules, offer sustained release, maintaining fish freshness for up to 48 hours at room temperature. Furthermore, purified CSLS exhibits low cytotoxicity and offers therapeutic benefits such as anti-inflammatory and oral ulcer healing properties. Despite these benefits, scalability, life cycle assessments (LCA), ecotoxicity in aquatic environments, and comprehensive consumer sensory acceptance remain critical gaps. This review outlines pathways to transition CSLS from pilot-scale applications to industrial-scale sustainable fisheries preservation.

Keywords: coconut shell, pyrolysis, fish; preservative

Introduction

The global food industry is undergoing a paradigm shift driven by rising consumer awareness and tightening regulatory scrutiny regarding the safety of synthetic food preservatives. Traditional chemical agents such as formaldehyde, sodium benzoate, sorbic acid, potassium sorbate, and sodium metabisulfite, while highly effective, but also are increasingly associated with potential health risks and environmental persistence. Consequently, food manufacturers and researchers are actively seeking natural, sustainable alternatives that do not compromise food safety. Fish and fishery products, owing to their high moisture content, neutral pH, and abundance of highly unsaturated fatty acids and proteins, represent some of the

most perishable commodities in the global food supply chain. Rapid post-harvest microbial spoilage and biochemical lipid oxidation not only limit shelf life but also present significant food safety risks, causing substantial economic losses across the seafood sector [1].

To mitigate these spoilage challenges, coconut shell liquid smoke (CSLS) has emerged as a highly viable bio-based alternative. CSLS is a liquid byproduct generated during the controlled thermal degradation (pyrolysis) of coconut shell waste. Coconut shells represent a substantial agricultural residue in Indonesia, one of the world's major coconut-producing countries, with national coconut production reaching approximately 2.84 million tonnes in 2024. The large volume of coconut processing consequently generates considerable quantities of coconut shell residues, which are often discarded or inefficiently burned, contributing to local air pollution. Valorizing these hard, lignocellulosic shells into high-value, food-grade preservatives directly aligns with circular economy principles and bio-based resource management [1], [2]. In addition to CSLS, the pyrolysis process generates bio-char and syngas, which can be further utilized as a solid carbonaceous material and a potential source of process heat or energy, respectively, thereby improving overall resource utilization. The resulting liquid smoke is naturally enriched with phenolic compounds, organic acids, and carbonyls, which jointly exert powerful antimicrobial and antioxidant activities. By integrating waste valorization with food preservation, CSLS offers a dual benefit: it reduces agricultural waste and provides a safe, highly functional preservative to maintain seafood quality [3].

Production Methodologies and Process Optimization

The chemical profile and functional properties of CSLS are heavily dictated by the thermochemical process its process parameters employed during thermal decomposition. Pyrolysis represents the core thermal conversion method, with technologies broadly categorized into conventional slow pyrolysis and modern microwave-assisted systems [4].

Conventional pyrolysis setups rely on external thermal heating to degrade coconut shells in the absence of oxygen. Typically, shells are heated within a temperature range of 250°C to 600°C over a duration of 1 to 3.5 hours [3], [5]. The distribution of liquid, solid, and gaseous products varies significantly with the peak temperature. Empirical studies establish that optimal total phenolic yields are achieved at temperatures between 450°C and 550°C. Within this thermal range, the degradation of lignin polymers accelerates, selectively yielding volatile phenolic compounds such as syringol and guaiacol, which are primary drivers of antioxidant and smoky sensory properties [3], [5], [6]. Under conventional slow pyrolysis, a highly optimized process configuration is established at a temperature of 450°C maintained for exactly 210 minutes [4].

Microwave-Assisted Pyrolysis (MAP) represents a major modern advancement over conventional thermal methods. MAP utilizes microwave radiation to induce rapid, volumetric heating within the biomass particles, bypassing the heat transfer limitations associated with conventional conduction and convection. This localized thermal degradation yields up to 34.6% liquid bio-oil, exhibiting significantly improved energy efficiency and reduced processing times [4], [7]. To optimize the conversion of microwave energy, activated carbon or charcoal is added as a microwave absorber. These carbonaceous sensitizers absorb microwave radiation exceptionally well, reaching pyrolysis temperatures rapidly and enhancing thermal selectivity toward active phenolic fractions [4], [8].

Operational parameters are highly critical to maximizing yield and quality in MAP. Investigations show that a reaction temperature between 255°C and 280°C, combined with a raw material particle size of 2 mm to 3 mm, optimizes the liquid smoke yield. This contrasts with conventional pyrolysis, which demands much higher temperatures (450°C) and longer process times (210 minutes) to overcome biomass thermal resistance [4]. Comparison between conventional and microwave-assisted pyrolysis can be seen in Figure 1.

To further refine the quality and chemical selectivity of CSLS, research has progressed toward microwave-assisted catalytic pyrolysis. By integrating solid catalysts, such as H-Beta

zeolites, into the microwave reactor, researchers can selectively increase desired hydrocarbon and phenolic yields while cracking heavy tar molecules. Response surface methodology (RSM) and factorial design have been extensively applied to model and optimize these complex multi-variable systems, ensuring reproducible production of highly active, low-tar bio-oils [7], [9].

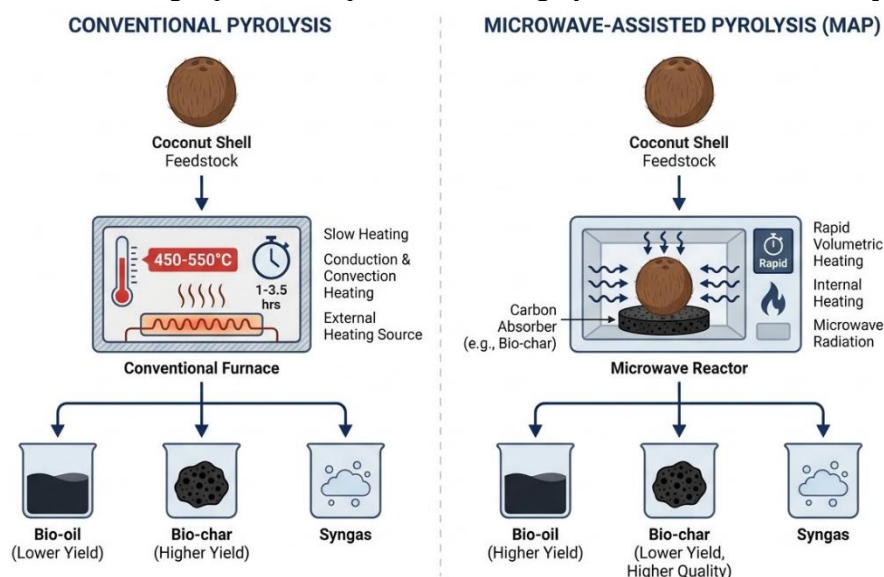


Figure 1. Comparison of coconut shell pyrolysis method.

Purification and Chemical Characterization

Raw liquid smoke generated directly from pyrolysis contains several undesirable constituents, including heavy wood tars, suspended solids, excessive organic acids, and carcinogenic polycyclic aromatic hydrocarbons (PAHs) like benzo[a]pyrene. Consequently, rigorous downstream purification is mandatory to render CSLS food-grade and toxicologically safe [10], [11].

Traditional purification protocols rely on successive redistillation and filtration steps. Redistillation utilizes different boiling points to separate high-boiling-point heavy tars and PAHs from volatile phenolics and acids. Following redistillation, active carbon filtration removes residual trace contaminants. This process successfully yields refined Grade A or Grade B liquid smoke, characterized by a light, clear color, high phenolic concentration, reduced acidity, and minimal to undetectable levels of harmful PAHs, complying with international standards for food safety [10], [11], [12]. Traditional purification process can be seen in Figure 2.

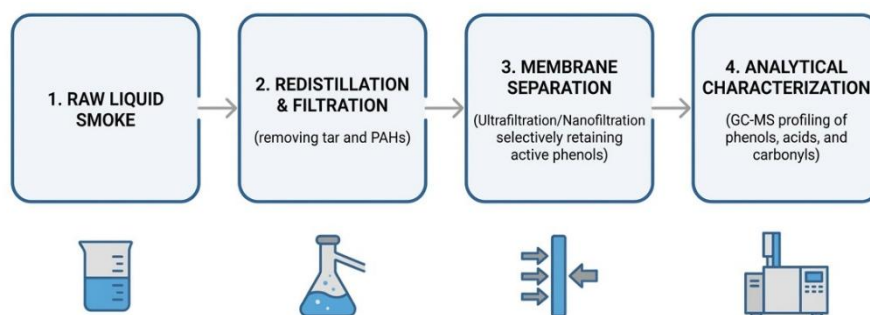


Figure 2. Traditional purification process of liquid smoke.

An emerging, highly precise alternative to thermal distillation is membrane separation. The application of ultrafiltration and nanofiltration membranes allows for pressure-driven, non-thermal separation of CSLS components. Membrane filtration can selectively retain or permeate specific fractions based on molecular size, allowing producers to remove heavy toxic compounds while selectively concentrating or tailoring the active phenol content for specialized preservation or food applications [12].

Standardized chemical profiling of CSLS relies on a suite of sophisticated analytical instruments. Gas Chromatography-Mass Spectrometry (GC-MS) is the primary technique used to identify and quantify the dominant phenolic compounds (guaiacol, syringol, phenol), organic acids (acetic acid), and carbonyls. Infrared (IR) Spectroscopy is routinely applied to characterize active functional groups (such as hydroxyl stretches in phenols and carbonyl bands), while Scanning Electron Microscopy (SEM) has been used in morphological studies to examine the structural impacts on biomass residue or encapsulation materials [10], [13].

Preservative Efficacy in Fish and Fishery Products

The fundamental commercial utility of CSLS resides in its robust preservation qualities. Marine and freshwater fish are highly susceptible to rapid post-harvest degradation, which CSLS actively slows through dual antimicrobial and antioxidant mechanisms.

CSLS displays broad-spectrum antimicrobial activity against both Gram-positive and Gram-negative bacteria, targeting critical spoilage organisms and foodborne pathogens such as *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Escherichia coli*. Laboratory assays demonstrate that CSLS exhibits Minimum Inhibitory Concentrations (MICs) as low as 0.22% to 0.40% for specific sensitive strains. In practical applications, incorporating CSLS at concentrations ranging from 2.5% to 7.0% effectively inhibits bacterial multiplication, thereby extending the shelf life of highly perishable products including fish balls, tuna fillets, tilapia fillets, and fish cakes under both ambient and refrigerated storage conditions [1], [14].

In addition to controlling microbial spoilage, CSLS is an exceptionally strong antioxidant. The dense population of phenolic compounds (guaiacol, syringol, and alkylated phenols) acts as primary hydrogen donors, successfully scavenging reactive DPPH free radicals and stopping the chain reaction of lipid oxidation. This antioxidant activity prevents the oxidation of highly sensitive polyunsaturated fatty acids (PUFAs) and slows the oxidative degradation of proteins, thereby preserving the nutritional value, structure, and chemical freshness of treated seafood during storage [1], [2], [15].

Advanced Delivery Systems: Coatings and Nanoencapsulation

While bulk application of CSLS via simple dipping or spraying at 2% to 5% is highly effective, advanced delivery systems have been developed to prolong efficacy and optimize sensory qualities [14], [16]. In edible coatings method, CSLS was combined with natural biopolymer coatings, specifically chitosan, creates a synergistic preservation barrier. Chitosan possesses native antimicrobial properties and forms a physical, semi-permeable film. Incorporating CSLS into these edible films further extends shelf life, limits moisture loss, and exhibits enhanced inhibitory control against stubborn Gram-negative bacterial species [16].

In the nanoencapsulation delivery system, a highly promising modern preservation strategy involves encapsulating CSLS inside nanocapsules fabricated from a matrix of chitosan and maltodextrin. These nanocapsules protect the volatile phenolic compounds from evaporation and degradation, enabling a controlled, sustained release of the active ingredients. Nanoencapsulated CSLS has been shown to maintain the freshness and chemical stability of catfish and tuna fillets for up to 48 hours at room temperature, dramatically outperforming raw liquid smoke applications, especially at concentration thresholds exceeding 5.0% [14], [17]. Edible coating process for fish through nanoencapsulation process can be seen in Figure 3.

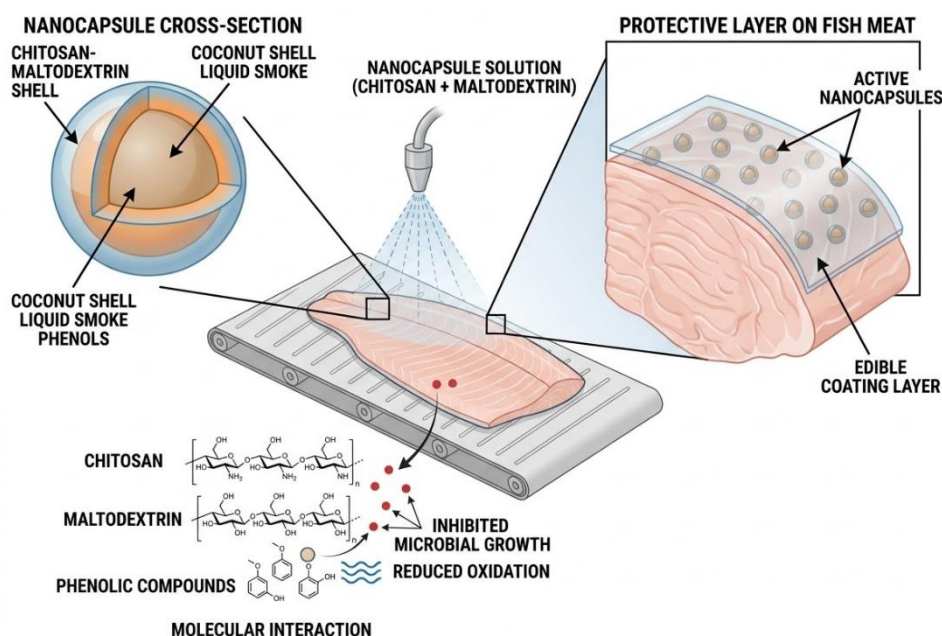


Figure 3. Active food preservation with nanocapsule coating process.

Antibacterial Mechanisms of Action

The potent antibacterial efficacy of CSLS is driven by multiple, concurrent biochemical and physical mechanisms, preventing bacteria from developing rapid resistance [2].

The primary mechanism of action involves the hydrophobic phenolic compounds partitioning directly into the lipid bilayer of the bacterial cell wall and cell membrane. This intrusion alters the membrane's physical structure, causing severe cellular disruption. The membrane loses its selective permeability, leading to the rapid, uncontrolled leakage of essential intracellular components such as vital proteins, nucleic acids, and potassium ions. Concurrently, these phenolics inhibit peptidoglycan synthesis, structurally weakening the bacterial cell wall and eventually causing cell lysis [2], [18].

Beyond structural membrane damage, the active constituents of CSLS cross the disrupted cell membrane and interact with the bacterium's genetic machinery. Transcriptomic and transcript analysis has revealed that phenolic compounds actively suppress the expression of genes responsible for essential bacterial metabolism, ATP synthesis, and critical virulence factors. By turning off these vital metabolic and virulence pathways, the bacterial cell is starved of energy and loses its capacity to colonize, replicate, or cause food spoilage [19].

Sensory, Comparative, and Multifunctional Attributes

The viability of any food preservative depends on its sensory compatibility, comparative efficacy against market standards, and safety profiles. CSLS exhibits unique, multifunctional benefits that extend beyond simple preservation.

At scientifically optimized application concentrations (typically 2.5% to 7.0%), CSLS successfully maintains or even enhances the core sensory attributes of treated fish, including color, flavor, and texture, without imparting undesirable off-flavors or excessive acidity. Furthermore, it stabilizes physicochemical properties during storage: it minimizes weight and moisture loss, stabilizes post-mortem pH, and restricts lipid and protein degradation [15], [20].

When evaluated against other common natural alternatives (such as wood vinegar or durian peel smoke), CSLS demonstrates comparable or superior preservation efficacy due to its extremely dense lignin-derived phenolic yield. Direct quantitative comparisons with synthetic standards, such as sodium benzoate or sorbic acid, are currently limited in scientific literature. However, the available data suggest that CSLS performs similarly or superiorly in reducing

microbial growth and lipid oxidation, offering a highly functional, non-chemical alternative to industry-standard synthetics [4], [21].

A highly unique aspect of CSLS is its range of biological activities that provide therapeutic value beyond food systems. In vitro and in vivo biomedical trials have demonstrated that CSLS possesses profound anti-inflammatory, antioxidant, and tissue-regenerative properties. Specifically, CSLS hydrogels have been shown to accelerate diabetic wound healing by promoting cell proliferation and tissue remodeling. Additionally, CSLS has proven highly effective in treating traumatic oral ulcers by accelerating the mucosal proliferation phase and alleviating local pain [22], [23], [24].

Safety, Toxicology, and Regulatory Status

Consumer safety is the primary benchmark for any natural food ingredient. Traditional wood smoking has long raised safety concerns due to the deposition of carcinogenic polycyclic aromatic hydrocarbons (PAHs) onto the food. However, purified CSLS presents an entirely different toxicological profile. Table 1 synthesizes the core aspects of CSLS preparation, efficacy, safety, and remaining research gaps, providing a quick reference for academic researchers and industry practitioners.

Table 1. core aspects of CSLS preparation, efficacy, safety, and remaining research gaps

Research Aspect	Summary of Empirical Findings	Key Empirical Parameters / References
Thermochemical Methods	Pyrolysis (conventional & microwave-assisted) optimized to maximize phenolic yield while limiting tar and acid formation.	Conventional: 450°C, 210 min MAP: 255-280°C, 2-3 mm particle size
Chemical Composition	Composed of phenols (antioxidants like guaiacol and syringol), organic acids (antimicrobial), and carbonyls (color/flavor).	GC-MS, IR, and SEM profiling; varies by temp
Preservative Efficacy	Strong antimicrobial/antioxidant activities. Effectively extends fish shelf life; nanoencapsulation dramatically enhances effects.	MIC: 0.22% - 0.40% Freshness preserved 48h at room temp
Mechanism of Action	Phenolic compounds partition into lipid bilayers, disrupting cell walls and causing leakage. Promotes genomic and metabolic suppression.	Inhibits peptidoglycan synthesis; suppresses virulence genes
Safety & Toxicology	Purified grades show exceptionally low PAH content and lower cytotoxicity compared to commercial/synthetic alternatives.	Grades A/B; meets food-grade PAH standards
Comparative Efficacy	Comparable or superior to other natural smoked extracts; direct quantitative benchmarks with synthetics remain scarce.	CSLS vs. sodium benzoate, sorbic acid, wood vinegar
Multifunctional Benefits	Exhibits strong anti-inflammatory, tissue-regenerating, and oral mucosal ulcer healing properties beyond food systems.	Diabetic wound hydrogels; mucosal proliferation phase
Research Gaps	Severe lack of Life Cycle Assessments (LCA), ecotoxicity profiles in aquatic systems, and comprehensive consumer acceptance models.	Future focus: LCA, ecotoxicity, regulatory standardization

By utilizing modern redistillation and membrane filtration technologies, manufacturers can selectively partition the chemical components of CSLS. Harmful, heavy PAHs (such as benzo[a]pyrene) are effectively separated out and reduced to levels that are completely

undetectable or far below strict regulatory limits. Consequently, purified Grade A and B liquid smokes meet or exceed stringent global safety standards for food additives, unlike traditional direct-smoked fishery products [25], [26].

Toxicological assays indicate that purified CSLS exhibits exceptionally low cytotoxicity. In comparative cellular studies, refined CSLS demonstrated significantly lower cytotoxicity than several common commercial liquid smokes and synthetic chemical preservatives. This excellent safety margin supports its application at functional, food-grade concentrations [22], [27].

Socio-Economic Barriers, Environmental Gaps, and Future Directions

While the chemical and preservative efficacy of CSLS is well-documented at laboratory and pilot scales, transitioning this technology to widespread industrial and commercial application in global fisheries faces multiple critical gaps and socio-economic hurdles.

The overwhelming majority of published studies operate at a laboratory or pilot scale. Widespread industrial adoption requires the scale-up of energy-efficient thermochemical processes, such as continuous Microwave-Assisted Pyrolysis (MAP) and catalytic pyrolysis. Furthermore, there is an absolute lack of comprehensive cost-benefit analyses or economic feasibility models comparing CSLS with inexpensive synthetic preservatives. Developing scalable production systems that small and medium enterprises (SMEs) can afford is crucial to establishing market viability [4], [28].

Although CSLS is promoted as a sustainable, waste-valorizing byproduct, there are currently no direct Life Cycle Assessment (LCA) studies comparing its environmental footprint to that of synthetic chemical preservatives. Crucially, empirical data regarding the biodegradability and potential ecotoxicological impacts of CSLS residues in aquatic environments are entirely lacking. Conducting rigorous LCA and ecotoxicity assays is imperative to confirm that wastewater streams from seafood processing facilities using CSLS do not harm surrounding aquatic ecosystems [1], [2], [29], [30].

Widespread food applications are contingent upon establishing definitive regulatory pathways. Producers must engage with national and international food safety authorities to standardize purification guidelines, explicitly setting maximum allowable limits for PAHs and other trace contaminants in CSLS-preserved foods. Simultaneously, while purified CSLS has been shown to maintain sensory quality, comprehensive, large-scale consumer sensory evaluations and market perception studies are urgently needed to ensure that consumers readily accept CSLS-treated products over traditional or untreated counterparts [20], [26], [31].

Conclusions

Coconut shell liquid smoke stands as a highly promising innovation at the intersection of food safety, environmental sustainability, and the circular economy. Produced through optimized pyrolysis and refined via modern purification technologies, CSLS contains active phenolics, organic acids, and carbonyls that provide powerful, dual antimicrobial and antioxidant protection. Its capacity to inhibit major spoilage bacteria (MICs as low as 0.22% to 0.40%) and stop lipid oxidation represents a highly effective natural preservation solution, extending seafood shelf life and maintaining key sensory attributes without harmful chemical residues. Advanced delivery systems like chitosan coatings and nanoencapsulation further enhance its physical stability and slow-release profile. To transition CSLS into a mainstream preservative, future research must move beyond laboratory-scale trials. Interdisciplinary investigations are required to model economic feasibility, quantify life cycle carbon and energy balances, map ecotoxicological impacts in wastewater, and establish clear international regulatory standards. By addressing these critical research gaps, CSLS can realize its full potential, transforming agricultural waste into a cornerstone of sustainable global fisheries preservation.

Acknowledgements

The authors would like to acknowledge Universitas Negeri Semarang for the funding of this study through DPA LPPM UNNES 2026 No. 822.8.4/UN37/PPK.11/2026

References

- [1] I. Zuraida and S. Budijanto, "Antibacterial activity of coconut shell liquid smoke (CS-LS) and its application on fish ball preservation," *Int. Food Res. J.*, vol. 18, no. 1, pp. 405–410, 2011
- [2] S. Harimurti, R. Fitrianiingsih, A. Eko Wibowo, and H. Widada, "Physical and Phytochemical Properties of Coconut Shell Liquid Smoke: Antibacterial and Antioxidant Alternative," in *E3S Web of Conferences*, 2024. doi: 10.1051/e3sconf/202459502009.
- [3] R. Silaban, J. P. Simanjuntak, B. H. Tambunan, and A. N. Putra, "Production and Characterization of Liquid Smoke from Coconut Shell Waste as an Effort to Reduce the Impact on Environmental Pollution," *Ecol. Eng. Environ. Technol.*, vol. 25, no. 7, pp. 162–170, 2024, doi: 10.12912/27197050/188389.
- [4] S. P. A. Anggraini *et al.*, "Improving Liquid Smoke Yield from Coconut Shells via Microwave-Assisted Pyrolysis With Selected Carbon Absorbents," *Rasayan J. Chem.*, vol. 19, no. 1, pp. 207–216, 2026, doi: 10.31788/RJC.2026.1919599.
- [5] Q. Dai, J. Li, Y. Cao, X. Wei, H. Tang, and J. Sun, "Pyrolysis of coconut cloth in a microwave reactor: Effect of pyrolysis parameters on product yield and characterization of liquid product and biochar," *BioResources*, vol. 15, no. 2, pp. 3737–3755, 2020, doi: 10.15376/biores.15.2.3737-3755.
- [6] E. Ganapathy Sundaram and E. Natarajan, "Pyrolysis of coconut shell: An experimental investigation," *J. Eng. Res.*, vol. 6, no. 2, pp. 33–39, 2009, doi: 10.24200/tjer.vol6iss2pp33-39.
- [7] S. Wang *et al.*, "Optimization of MCP process of coconut cloths by response surface method and composition analysis of bio-oil product," *Biomass Convers. Biorefinery*, vol. 14, no. 2, pp. 2321–2331, 2024, doi: 10.1007/s13399-022-02346-y.
- [8] S. P. A. Anggraini, S. Suprpto, S. R. Juliastuti, and M. Mahfud, "Optimization of pyrolytic oil production from coconut shells by microwave-assisted pyrolysis using activated carbon as a microwave absorber," *Int. J. Renew. Energy Dev.*, vol. 13, no. 1, pp. 145–157, 2024, doi: 10.14710/ijred.2024.56287.
- [9] X. Wei *et al.*, "Catalytic pyrolysis of coconut shell: a study on product distributions, optimized response surface methodology, and catalytic mechanism of bio-oil production," *Biomass Convers. Biorefinery*, vol. 13, no. 8, pp. 6761–6776, 2023, doi: 10.1007/s13399-021-01653-0.
- [10] E. Budi, "Liquid Smoke of Coconut Shell," in *AIP Conference Proceedings*, 2024. doi: 10.1063/5.0183410.
- [11] H. Susanto, N. Rokhati, A. M. I. Filardli, M. H. Robbani, Q. Anggraini, and T. Istirokhatun, "Improving the quality of liquid smoke by filtration using membranes," *Food Res.*, vol. 8, pp. 136–144, 2024, doi: 10.26656/fr.2017.8(S1).11.
- [12] A. K. Effendi, B. Piluharto, D. Indarti, and A. W. Pratama, "Physical and Chemical Components Characteristics of Liquid Smoke Redistillation from Different Biomass Sources," *ASM Sci. J.*, vol. 18, pp. 1–5, 2023, doi: 10.32802/ASMSCJ.2023.1442.
- [13] M. Azhar, S. Solechan, R. Saraswati, P. Suharso, S. Suhartoyo, and B. Ispriyarso, "The New Renewable Energy Consumption Policy of Rare Earth Metals to Build Indonesia's National Energy Security," *E3S Web Conf.*, vol. 68, pp. 1–10, 2018, doi: 10.1051/e3sconf/20186803008.
- [14] S. Saloko, P. Darmadji, B. Setiaji, and Y. Pranoto, "Antioxidative and antimicrobial activities of liquid smoke nanocapsules using chitosan and maltodextrin and its application on tuna fish preservation," *Food Biosci.*, vol. 7, pp. 71–79, 2014, doi: 10.1016/j.fbio.2014.05.008.
- [15] O. Bouzgarrou, R. Baron, and S. Sadok, "Determination of the quality of liquid smoked tilapia fillets based on physicochemical analysis," *J. Food Meas. Charact.*, vol. 14, no. 2, pp. 978–991,

- 2020, doi: 10.1007/s11694-019-00347-6.
- [16] M. Faisal, F. M. Djuned, Y. Abubakar, and H. Desvita, "Chikuwa preservation by edible coating from a combination of young coconut shell liquid smoke and chitosan," *South African J. Chem. Eng.*, vol. 50, pp. 135–142, 2024, doi: 10.1016/j.sajce.2024.07.013.
- [17] F. Swastawati, A. N. Al-Baari, E. Susanto, and L. Purnamayati, "The effect of antioxidant and antibacterial liquid smoke nanocapsules on catfish fillet (*pangasius* sp.) during storage at room temperature and cold temperature," *Carpathian J. Food Sci. Technol.*, vol. 11, no. 4, pp. 165–175, 2019, doi: 10.34302/2019.11.4.16.
- [18] F. Azi, Z. Li, P. Xu, and M. Dong, "Transcriptomic analysis reveals the antibacterial mechanism of phenolic compounds from kefir fermented soy whey against *Escherichia coli* 0157:H7 and *Listeria monocytogenes*," *Int. J. Food Microbiol.*, vol. 383, 2022, doi: 10.1016/j.ijfoodmicro.2022.109953.
- [19] D. Shiyu, S. Xu, J. Jianming, and W. Hua, "Botanical cosmetic ingredients (VIII) Research and development of plant antibacterial," *China Surfactant Deterg. Cosmet.*, vol. 54, no. 4, pp. 385–392, 2024, doi: 10.3969/j.issn.2097-2806.2024.04.003.
- [20] R. Köklü, H. Turan, C. O. Altan, D. Kocatepe, B. Köstekli, and B. Corapci, "The Sensory, Chemical and Microbiological Quality of Sous-Vide Cooked Sea Bass (*Dicentrarchus labrax* Linnaeus, 1758) With Liquid Smoke Flavor," *Food Sci. Nutr.*, vol. 14, no. 8, 2026, doi: 10.1002/fsn3.72184.
- [21] S. S. Achmadi, N. R. Mubarik, R. Nursyamsi, and P. Septiaji, "Characterization of redistilled liquid smoke of oil-palm shells and its application as fish preservatives," *J. Appl. Sci.*, vol. 13, no. 3, pp. 401–408, 2013, doi: 10.3923/jas.2013.401.408.
- [22] N. F. Ayuningtyas *et al.*, "The role of liquid smoke coconut shell in the proliferation phase of an oral traumatic ulcer," *J. Pharm. Pharmacogn. Res.*, vol. 8, no. 6, pp. 549–557, 2020, [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85091511662&partnerID=40&md5=14b4f49a96bc3cc9d512e6b61fd8c158>
- [23] M. Masfria *et al.*, "Histopathological and immunohistochemical evaluation of the impact of coconut shell-derived liquid smoke hydrogel on diabetic wound healing," *J. Appl. Pharm. Sci.*, vol. 15, no. 12, pp. 104–116, 2025, doi: 10.7324/JAPS.2025.v15.i12.11.
- [24] M. D. C. Surboyo *et al.*, "The cytotoxicity, anti-inflammation, anti-nociceptive and oral ulcer healing properties of coconut shell liquid smoke," *J. HerbMed Pharmacol.*, vol. 10, no. 4, pp. 459–467, 2021, doi: 10.34172/jhp.2021.53.
- [25] C. T. Nithin *et al.*, "Source-dependent compositional changes in coconut flavoured liquid smoke and its application in traditional Indian smoked fishery products," *Food Addit. Contam. - Part A Chem. Anal. Control. Expo. Risk Assess.*, vol. 37, no. 10, pp. 1610–1620, 2020, doi: 10.1080/19440049.2020.1798030.
- [26] A. S. Pimenta, M. Fasciotti, T. V Monteiro, and E. Costa de Souza, "Chemical profiling of liposoluble liquid smokes obtained from Eucalyptus wood tar: confirmation of absence of polycyclic aromatic hydrocarbons," *Food Addit. Contam. - Part A Chem. Anal. Control. Expo. Risk Assess.*, vol. 37, no. 6, pp. 882–894, 2020, doi: 10.1080/19440049.2020.1740337.
- [27] C. S. Reshma *et al.*, "Extraction, chemical characterization, antimicrobial, and antioxidant properties of liquid smoke derived from locally sourced wood sawdust," *Int. J. Biol. Macromol.*, vol. 323, 2025, doi: 10.1016/j.ijbiomac.2025.147189.
- [28] A. W. Putranto, A. Oktaviani, and F. P. Puspaningarum, "Coconut shell-liquid smoke production based on the redistillation-filtration technology and its characterisation," in *IOP Conference Series: Earth and Environmental Science*, 2020. doi: 10.1088/1755-1315/475/1/012039.
- [29] D. N. H. B. A. Razak, N. A. Kamal, and G. Lee, "Life Cycle Assessment of Activated Carbon from Waste Materials as an Adsorbent in Wastewater Treatment," *J. Kejuruter.*, vol. 36, no. 4, pp. 1699–1709, 2024, doi: 10.17576/jkukm-2024-36(4)-32.
- [30] I. Purnama *et al.*, "Pyrolytic wood vinegar from industrial crop residues as a bio-based fungicide

- for Fusarium control in banana cultivation,” *Ind. Crops Prod.*, vol. 242, 2026, doi: 10.1016/j.indcrop.2026.122909.
- [31] A. Gani, M. Adlim, R. F. I. Rahmayani, L. Hanum, and R. Nabila, “Preparation and characterization of coconut shell liquid smoke and the properties of preserving tofu,” *Kuwait J. Sci.*, vol. 51, no. 4, 2024, doi: 10.1016/j.kjs.2024.100289.