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# UTILIZATION OF LIGNOCELLULOSIC WASTE AS A SOURCE OF LIQUID SMOKE: A LITERATURE REVIEW

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## *Abstract*

***Introduction:*** *Lignocellulosic biomass waste will become a problem for environmental health if not managed correctly. Biomass waste decomposition can produce methane gas which impacts climate change; it can also be a source of breeding pests and diseases. Various efforts have been made to utilize the waste so that it has an added economic value and is environmentally friendly. One of the waste utilization techniques is the carbonization of lignocellulosic biomass into charcoal and liquid smoke.* ***Discussion:*** *A literature review used the articles from Science Direct, Pubmed, Google Scholar, and Research Gate databases over ten years. This literature review paper aims to provide information on producing and utilizing liquid smoke and concludes with some suggestions on production and application. The literature review results show evidence that liquid smoke has been used since the time of the Neanderthals. Then, since the early nineteen century, liquid smoke has been applied in agriculture as plant growth, soil treatment, pesticide, antimicrobial, rubber coagulant/deodorizer, and antioxidant.* ***Conclusion:*** *A significant contribution of liquid smoke utilization is all lignocellulosic biomass waste that can be carbonized into charcoal and liquid smoke so that it can reduce waste problems. Therefore, liquid smoke can reduce the use of pesticides, herbicides, and insect repellents made from synthetic chemicals that can poison the environment. Not much research has been produced and utilized liquid smoke in the pyrolysis temperature stratification technique. So, there are still quite a lot of research opportunities for the diversification of liquid smoke production.*

## INTRODUCTION

Lignocellulosic substances are plant biomass with a large portion on earth, produced from photosynthesis processes and capable of renewable resource feedstock. Lignocellulosic contains cellulose, hemicellulose, lignin, and extractive (1–2). Agriculture, plantations, and forestry are sources of lignocellulosic biomass, which also produce large amounts of biomass waste such as parts of stems, bark, twigs, branches, leaves, and roots. If the waste is not handled correctly, it will result in biomass decay, which becomes a breeding ground for pests and diseases, causing odor pollution and producing methane gas from anaerobic decomposition, contributing to climate change (3–4). This condition will impact the health of the environment and society. As a branch of public health, environmental health refers to evaluating and managing environmental factors that can influence human health. Various efforts have been made to overcome biomass waste, such as biofuels, handicrafts, fertilizers, chemical sources, charcoal, and liquid smoke (4–6).

Literature review analysis of liquid smoke production that uses pyrolysis temperature stratification technique and its utilization has been found fewer than pyrolysis on one-stage temperature (not stratification temperature). Liquid smoke utilization generally uses high

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pyrolysis at 350-500 ºC, with very high phenol and acid content. It is suitable for antimicrobial activity, reducing smell pollution, and herbicide purposes. However, for seed and plant growth, it must be dilution with some water to avoid plant phytotoxic. Improper dilution will damage the plants. So, how is the development of research on liquid smoke production through pyrolysis temperature stratification, and whether the pyrolysis temperature stratification gives a positive response to the seed/plant treatment? Therefore, this study aimed to explore the technology for producing and utilizing liquid smoke from biomass waste, especially pyrolysis temperature stratification technique production. Also, share knowledge for the community in lignocellulosic waste control and obtain added value from liquid smoke production for environmental health.

## DISCUSSION

A literature review was used to obtain a comprehensive, critical, and objective analysis of the utilization of liquid smoke from lignocellulosic biomass waste by summarizing the facts from scientific articles. The inclusion criteria for the scientific article search are articles derived from peer-reviewed journals; original research published from 2012 to 2022 in English or Indonesian; conducted in any country; case studies, full-text and original research articles on production, chemical properties characterization, and utilities of liquid smoke in agriculture, animal husbandry, food, and health sector, open access journal, Scopus or Sinta index. The article was collected from Science Direct, Pubmed, Google Scholar, and Research Gate databases. The literature review keywords were: lignocellulosic biomass, production, utilization of liquid smoke/wood vinegar/pyrolignous acid, and pyrolysis/carbonization. The limitation of this review is that there may be unrecorded articles in searching. In this review, the challenge and difficulty are getting journals according to the keyword pyrolysis temperature stratification because "temperature stratification" is a term that has not been widely used. The literature review articles were then synthesized by grouping similar extraction data to answer the research aims. The collected article from various library sources is then analyzed and verified for similarities or differences for further discussion by screening the abstract and the method of the article. Some articles were excluded because they did not meet the required inclusion criteria.

There are 37 articles analyzed, 33 published by international and four by national journals. The research sites were Indonesia, Malaysia, Thailand, China, Uganda, Turkey, Brazil, Colombia, Netherlands, Spain, Sweden, England, and Canada. Data analysis is presented descriptively and tabulated by synthesizing, summarizing, and comparing research data variables (Table 1).

**Table 1: Journal Review**

| Author | Title | Method | Sample | Result | Summary |
|---|---|---|---|---|---|
| Supin Sangsuk, Sirisak Suebsiri, Pongsakorn Puakhom (11) | The metal kiln with heat distribution pipes for high quality charcoal and wood vinegar production. | Experimental study | Bamboo (*Thyrsostachys siamensis*, 30% MC). Metal kiln. Temp. 500-600ºC. 27 hour | The experiment gave 315 kg charcoal and 900 l of crude bamboo vinegar. Bamboo charcoal showed 8.5% of MC, 7.7% of VM, 81% of FC, and 11.3% of Ash. Only 360 L of wood vinegar without tar has a pH of 3. | Charcoal production using the metal kiln-HDP gained high profit and is possible for commercialization. |
| Hennius A. (14) | Viking Age tar production and outland exploitation | Historical study | Some provinces in Sweden | The recent excavations in Sweden revealed the technique of tar production on a large scale, which appeared in the eighth century AD. | The production of tar from wood dates far into Scandinavian prehistory. At that time, Scandinavian society's focus on intensified marine and the sailboat. This condition most probably drove the increase in tar production, which was used for protecting wood, sealing and filling out the wood of sailboats, and as a trade product. |
| Komarayati, S Gusmailina Pari, G.(83) | Arang dan cuka Kayu: Produk hasil hutan bukan kayu untuk meningkatkan pertumbuhan tanaman dan serapan hara karbon | Experimental study | Charcoal and liquid smoke from mixed wood sawdust (unknown process). | Adding 20% charcoal to the soil media (w/w) and adding 1% concentration of liquid smoke (sprayed on soil media) can increase the height growth of sengon seedlings by 208%. In contrast, the addition of liquid smoke concentrations of 2%, 3% and 4% were 123%, 154%, and 117%, respectively, compared to the control. | A mixture of charcoal and liquid smoke at certain concentrations can increase the growth of forest plant seedlings. |

| Author | Title | Method | Sample | Result | Summary |
|---|---|---|---|---|---|
| Komarayati S, Wibowo S (40) | Karakteristik asap cair dari tiga jenis bambu | Experimental study | Black bamboo, tutul bamboo & betung bamboo (60-75 kg) Temp: 400-450 ºC. Time: 32-96 hours. | The yield of liquid smoke from black and tutul bamboo using a spiral condenser, i.e. 5-6%, and betung bamboo using a straight pipe condenser of 24%. | The different types of the condenser in the drum reactor model give different yields of liquid smoke |
| Omulo G, Willett S, Seay J, Banadda N, Kabenge I, Zziwa Al. (41) | Characterization of slow pyrolysis wood vinegar and tar from banana wastes biomass as potential organic pesticides. | Experimental study | The banana wastes, i.e., leaves, pseudostem, & peels (0.2-0.8 kg) Temp: 350-550 ºC, Time: 45-90 minutes | With the slow pyrolysis process, banana wastes can be used for charcoal and vinegar products. The chemical composition of banana waste vinegar was acids (69%), alcohols (63%), ketones (28%), phenols (26%), and furans (22%). | Banana vinegar and tar have chemical compounds beneficial for agriculture and chemical industries, i.e., acids, furan, ketones, alcohols, and phenols. The compounds could be used as pesticides, insecticides, biocides, antimicrobial agents, and soil conditioners. |
| Lu X, Jiang J, He J, Sun K, Sun Y. (42) | Effect of pyrolysis temperature on the characteristics of wood vinegar derived from Chinese fir waste: A comprehensive study on its growth regulation performance and mechanism. | Experimental study | Chinese fir wood (20 g). Temp: 150-350 ºC | The chemical constituents of Chinese fir WVs were affected by pyrolysis temperature. The WV collected from 20 to 150 °C exhibited a promoting effect on wheat seed germination and root growth. | The low temperature of pyrolysis produces wood vinegar that promotes wheat seed germination and root growth, but WV from high temperature inhibits the seed growth. |
| Mahdie MF, Violet V, Helmi M.(18) | Rendement and characteristics of wood vinegar produced from ironwood delinquent waste through clay kiln charcoaling furnace | Experimental study | Ironwood (49.9 tons) Temp:400-600 ºC, Time: 21 days) | The charcoal and wood vinegar yield from ironwood waste was 14% and 0.05%, respectively. The characteristic of wood vinegar was a pH of 3.63, specific gravity of 1.012, and an acid value of 3.73%. | A Clay Kiln reactor in big capacity (50 tons) gives good rendement of charcoal (14%) but a small yield of ironwood wood vinegar (0.05%) |
| Wibowo S. (43) | Characteristic of smoke liquid from nyamplung shell | Experimental study | Nyamplung shell (3-4 kg), Temp.200, 300, 400-500 ºC, time: 5-7 hours | The carbonization at 500 ºC in 5 hours gives the highest yield, i.e., 45.5%, specific gravity 1.009, phenol 3.95%, and an acid value of 9.5%. | The one-stage carbonization will give a high rendement of wood vinegar at the highest temperature because wood vinegar will collect from the first time wood vinegar is produced (100 ºC) to the highest temperature (500 ºC) without interruption until the last process. |
| Pimenta AS, Monteiro TVC, Lima KMG. (19) | Chemical composition of pyroligneous acid obtained from eucalyptus GG100 clone | Experimental study | The wood of *Eucalyptus urophylla*, *Eucalyptus grandis* (500 g) Temp. 450 ºC. Time: 30 minutes | Dichloromethane, ethyl acetate, and diethyl ether could extract 67, 75, and 55 compounds, respectively, from re-distillate Eucalyptus wood vinegar, with the phenolic compound as the primary group, followed by aldehyde, ketone, furan, pyran, and ester. | The slow pyrolysis product from E.urophylla and E. grandis could be extracted by some solvent, i.e., dichloromethane, diethyl ether, and ethyl acetate, to get more chemical compounds than crude wood vinegar. |
| Faisal M, Gani A. (20) | The effectiveness of liquid smoke produced from palm kernel shells pyrolysis as a natural preservative | Experimental study | of palm kernel shells Temp. 340, 360, and 380°C. | The purified liquid smoke (380 ºC) on two-stage distillation got the smallest TVB value (12.66 mgN/100 g) on 20 hours of fish balls preserved using a 3% concentration of liquid smoke. But on 2% concentration, the respondents preferred the fish balls' taste, aroma, and texture. | The palm kernel shells liquid smoke could be used as an alternative preservative for fish balls. The liquid smoke produced at a high temperature, 380 ºC, and a higher concentration of 3% proves more effective as an antimicrobial agent than a low pyrolysis temperature. |
| Desvita H, Faisal M. (21) | Edible coating for beef preservation from chitosan combined with liquid smoke | Experimental study | Rice hulls. Temp. 300, 340, 380 °C. Time: 2 hours | The 3% concentration of rice hull liquid smoke that was produced at 300 C and 380 C combined with 1.5% chitosan gave the beef texture did not change until the fourth-day storage | Combining rice hulls liquid smoke and chitosan as the edible coating can be used as beef preservatives. |
| Wang Y, Qiu L, Song Q, Wang S, Wang Y, Ge Y. (17) | Root proteomics reveals the effects of wood vinegar on wheat growth and subsequent tolerance to drought stress | Experimental study. | Wheat (Triticum aestivum L.) seeds and unknown wood vinegar | The presoaked of wheat seed with wood vinegar can enhance TCA cycle speed in wheat roots to enable them to cope with subsequent drought stress. Furthermore, WV can start an early defence mechanism to mitigate drought stress on wheat roots. | An appropriate wood vinegar concentration on pretreatment soaking of wheat seed significantly promotes seedling and root growth. It can act as an early defence mechanism to mitigate subsequent drought stress and maintain cellular metabolism's stability. |

| Author | Title | Method | Sample | Result | Summary |
|---|---|---|---|---|---|
| Zhu K, Gu S, Liu J, Luo T, Khan Z, Zhang K, et al. (51) | Wood vinegar as a complex growth regulator promotes the growth, yield, and quality of rapeseed | Experimental study | Wood vinegar from poplar wood (unknown process) | The poplar liquid smoke at 0.25% concentration can increase the rapeseed plant, i.e., seed yield, leaf area index, and the number of pods by 9.6%, 23.5%, and 24%, respectively, compared to the control. | The application of liquid smoke on crop growth and yield is of great importance to sustainable agriculture, crop ecology, and environmental protection. |
| Mungkunkamchao T, Kesmala T, Pimratch S, Toomsan B, Jothityangkoon D. (52) | Wood vinegar and fermented bioextracts: Natural products to enhance the growth and yield of tomato (*Solanum lycopersicum* L.) | Experimental study | liquid smoke from Eucalyptus wood, an unknown process | The application of liquid smoke (0.125% concentration) and fermented bioextract (0.2% concentration), alone or in combination, gave small increases in fruit number, the weight of fresh fruit, and the weight of the total dry plant, but total soluble solutes of tomato fruit was significantly enhanced. | Liquid smoke can be mixed with fermented bio extracts and has similar effects on tomato plants. Both liquids can be used in foliar sprays or as soil drenches. |
| Polthanee A, Kumla N, Simma B. (53) | Effect of Pistia stratiotes, cattle manure and wood vinegar (pyroligneous acid) application on growth and yield of organic rainfed rice | Experimental study | Eucalyptus liquid smoke (unknown process) | Applying Eucalyptus liquid smoke (0.33% concentration) and combined cattle manure can improve the number of panicles per hill and give paddy plants the maximum grain yield (2,4 kg ha-1). | Liquid smoke combined with cattle manure significantly increased grain yield compared with liquid smoke alone. |
| Chen J, Wu JH, Si HP, Lin KY. (54) | Effects of adding wood vinegar to nutrient solution on the growth, photosynthesis, and absorption of mineral elements of hydroponic lettuce | Experimental study | Liquid smoke (unknown process) | Growth rates, water, mineral elements absorption, and photosynthesis were low in lettuce grown in a nutrient solution with 1 ml of L-1 wood vinegar. However, lettuce grown in a solution with 0.25 ml L-1 wood vinegar did not show a significant difference from the control group. | A liquid smoke concentration of 0.25 ml L-1 was sufficient to maintain the pH of the nutrient solution within the optimal range for growth. |
| Nunkaew T, Kantachote D, Chaiprapat S, Nitoda T, Kanzaki H. (55) | Use of wood vinegar to enhance 5-aminolevulinic acid production by selected Rhodopseudomonas palustris in rubber sheet wastewater for agricultural use | Experimental study | Liquid smoke (unknown species n process) | The addition of liquid smoke (0.63% concentration) for R. palustris strains TN114 and LS 1.25% concentration for R. palustris strains PP803 and the mixed culture significantly increased the ALA content by 3.7–4.2 times compared to controls. | Liquid smoke can be used as a source of levulinic acid combined with a non-sterile latex rubber sheet wastewater and microbe Rhodopseudomonas palustris. Adding liquid smoke will reduce the production cost of levulinic acid 31 times. |
| Ofoe R, Gunupuru LR, Wang-Pruski G, Fofana B, Thomas RH, Abbey, Lord. (56) | Seed priming with pyroligneous acid mitigates aluminum stress, and promotes tomato seed germination and seedling growth. | Experimental study | Liquid smoke from white pine (unknown process) | Tomato seed priming with liquid smoke (2% concentration) for 24 hr significantly enhanced seed germination and seedling growth. Also, liquid smoke can increase root volume, fresh seedling weight, and the total lengths and surface areas of seedling hypocotyls and roots. | Liquid smoke can be used as seed priming that mitigates aluminum stress and improves tomato seed germination and seedling growth by improving antioxidant defence against Al-induced oxidative stress. |
| Aguirre JL, Baena J, Martín MT, Nozal L, Gonzales S, Manjon JL, Painado M (61) | Composition, ageing and herbicidal properties of biomass pyrolysis | Experimental study | Liquid smoke from pine & poplar wood, pruning waste.Temp. 450-500 ºC | The sprayed liquid smoke in concentrations of 50, 75, and 100 % was effective against all plant weeds. | The liquid smoke in high concentrations of 50 to 100% can be used as herbicide against weeds. |
| Liu X, Sun H, Gao P, Liu C, Ding X. (62) | Antioxidant properties of compounds isolated from wood vinegar by activity-guided and pH- gradient extraction. | Experimental study | Liquid smoke from *Pinus tabulaeformis Carr*. (unknown process) | The extraction liquid smoke using dichloromethane gives the highest total phenolic content than other extracts. There are seven phenols isolated from liquid smoke for an antioxidant test. All the compounds showed potent antioxidant activities in the DPPH, ABTS, and FRAP assays. | Liquid smoke consists of a phenols compound that has the potential as an antioxidant agent. |
| Li R, Narita R, Nishimura H, Marumoto S, Yamamoto SP, Ouda R, et al.(63) | Antiviral activity of phenolic derivatives in pyroligneous acid from hardwood, softwood, and bamboo. | Experimental study | Liquid smoke from hardwood, softwood and bamboo | The total amount of phenolic compounds in liquid smoke from bamboo is higher than softwood and hardwood. The number of phenolic hydroxyl groups significantly affects the antiviral activity, and catechol and its derivatives exhibit higher viral inhibition effects than other phenolic derivatives. | The liquid smoke from hardwood, softwood, and bamboo significantly disinfected encephalomyocarditis virus (EMCV). |

| Author | Title | Method | Sample | Result | Summary |
|---|---|---|---|---|---|
| Li R, Narita R, Ouda R, Kimura C, Nishimura H, Yatagai M,Fujita T and Watanabe T (64) | Structure-dependent antiviral activity of catechol derivatives in pyroligneous acid against the encephalomycarditis virus | Experimental study | Liquid smoke from *Larix kaempferi* wood (unknown process) | The liquid smoke from Japanese larch showed potent antiviral activity against the encephalomycarditis virus (EMCV). Catechol, 3-methyl-, 4-methyl-, 4-ethyl-, 3-methoxycatechol, and 2-methyl-1,4-benzenediol were significant antiviral compounds. | The liquid smoke from Japanese larch, especially catechol and its derivatives with different substituent groups, showed solid antiviral activity against EMCV. |
| Chukeatirote E, Jenjai N. (65) | Antimicrobial activity of wood vinegar from Dimocarpus longan. | Experimental study | Longan wood liquid smoke (unknown process) | The longan liquid smoke (12.5%, 25% and 50% concentration) showed antibacterial activity against 14 bacterial strains tested. But liquid smoke only inhibited one fungus strain, i.e. *Candida albicans*. | The antimicrobial activity of liquid smoke is generally effective against microbial in the high concentration (>10% concentration). |
| Suresh G, Pakdel H, Rouissi T, Brar SK, Fliss I, Roy C. (66) | In vitro evaluation of antimicrobial efficacy of pyroligneous acid from softwood mixture. | Experimental study | Combination of 80% pine wood and 20% fit+spruce. Temp. 475 ºC | Neutralized liquid smoke (add some NaOH 12 M until pH 7.0) gave higher antibacterial activity than liquid smoke acidic (pH 3.7). Meanwhile, acidic liquid smoke is more effective for fungal strains than neutralized liquid smoke. | Liquid smoke from a pine, spruce, and fir wood mixture was evaluated for antibacterial and antifungal activity in acidic pH and neutral pH (add some NaOH 12 M until pH 7.0). Both liquids can be used for antimicrobial activity |
| Hagner M, Tiilikkala K, Lindqvist I, Niemelä K, Wikberg H, Källi A. (66)(67) | Performance of liquids from slow pyrolysis and hydrothermal carbonization in plant protection. | Experimental study | Liquids smoke from pine bark, pine forest residues, wheat straw, and willow | Liquids smoke from pine bark, pine forest residues, wheat straw, and willow, produced with slow pyrolisis and hydrothermal carbonization. The most effective pesticidal test is willow liquid smoke from a slow pyrolysis process, but hydrothermal carbonization did not effective for pesticidal activity. | Liquid smoke can produce using a hydrothermal carbonization process but has a low concentration of organic compounds compared to liquid smoke from a slow pyrolysis process. |
| Wang HF, Wang JL, Wang C, Zhang WM, Liu JX, Dai B. (68) | Effect of bamboo vinegar as an antibiotic alternative on growth performance and fecal bacterial communities of weaned piglets. | Experimental study | Liquid smoke from bamboo (unknown process) | The higher concentration of bamboo liquid smoke (0.8%) tended to decrease the richness and Shannon index of intestinal bacterial communities in piglets' faecal compared to the control and lower concentration of 0.2% and 0.4% | The liquid smoke from bamboo in feed exerts, in a certain amount, an effect on the faecal bacterial community of piglets. The liquid smoke acts like an antibiotic in the piglet diet and can be an alternative antibiotic. |
| Pangnakorn U, Kanlaya S, Kuntha C. (69) | Effect of wood vinegar for controlling houseflies (Musca domestica L .) | Experimental study | Liquid smoke from wood waste. Temp. 430 ºC | With the increase in liquid smoke concentration and exposure time, larval mortality increased. The highest mortality is found in the 30% concentration. | Liquid smoke can be used as housefly larvicidal at high concentrations (30%) on the feeding technique. |
| Akkuş M, Akçay Ç, Yalçın M. (70) | Antifungal and larvicidal effects of wood vinegar on wood-destroying fungi and insects | Experimental study | Oakwood liquid smoke. Temp. 350 ºC | Liquid smoke at 6% concentration gave the lowest mass loss on impregnated liquid smoke wood samples causing attack by white-rot and brown-rot fungi. Furthermore, a 6% concentration can inhibit mould growth attack for three weeks and 100% mortality to *Hylotrupes bajulus* larvae after 16 weeks. | The oak wood liquid smoke can use as wood protection (impregnation material) that can inhibit fungal and mould, as well as anti-larvicidal for *Hylotrupes bajulus* larvae. |
| Cai K, Jiang S, Ren C, He Y. (71) | Significant damage-rescuing effects of wood vinegar extract in living Caenorhabditis elegans under oxidative stress. | Experimental study | Liquid smoke from hickory shell. Temp. 280 ºC | Liquid smoke prolongs the lifespan and increases the brood size in reactive oxidative species (ROS)-sensitive mutant worms. | Liquid smoke at 0.05%, 0.25% and 0.5% concentration exhibits a curative effect on ROS-sensitive mutants on wild-type worms under oxidative stress |
| Khai LTL, Nghia NT, Hayashidani H (72) | Study on effectiveness of activated charcoal and wood vinegar on prevention of piglet diarrhea. | Experimental study | Liquid smoke (no process information) | The mixture of liquid smoke and activated charcoal (2 ml/1kg: 8 g) in feed gave a lower average ratio of diarrhoea in suckling pigs and post-weaning pigs compared to control groups. | Applying liquid smoke (0.2% concentration) and activated charcoal (8 g) in feed (per kg) can prevent diarrhoea in pigs (suckling and post-weaning) in both rainy and dry seasons |
| Oramahi HA, Yoshimura T. (73) | Antifungal and antitermitic activities of wood vinegar from *Vitex pubescens* Vahl. | Experimental study | Laban wood liquid smoke. Temp. 350, 400, 450 ºC | Liquid smoke from pyrolysis at 450 ºC has higher activity against white-rot and brown-rot fungi than at 400 and 350 ºC. Besides that, the 450 ºC on 3% concentration showed 100% mortality for *Reticulitermes speratus* termite and needed 10% to 100% mortality for *Coptotermes formosanus* termite.. | Liquid smoke from laban wood can use for antifungal and antitermitic activities that produce from high-temperature pyrolysis. |

| Author | Title | Method | Sample | Result | Summary |
|---|---|---|---|---|---|
| Zhou L, Zhang W, Shi C, Li M, Peng D, Liu F. (74) | The potential of cotton stalk wood vinegar in mitigating CO 2 and CH 4 emissions from cattle manure composting: Pilot study. | Experimental study | Cotton stalk (2 kg). Temp. 500 ºC, 2 hours | The addition of liquid smoke from cotton stalks in composting of cow manure significantly raised the temperature and decreased the composting period. The liquid smoke in 3% concentration will reduce 15% methane gas. | The cotton stalk liquid smoke can use for mitigating CH4 and CO2 emissions from cattle manure composting. |
| Wang B, Li D, Yuan Z, Zhang Y, Ma X, Lv Z, Xiao Y, Zhang J (76) | Evaluation of joint effects of perfluorooctane sulfonate and wood vinegar on planarians, *Dugesia japonica* | Experimental study | Liquid smoke from waste wood | The liquid smoke, even in low concentration, can reduce malondialdehyde levels, increase the activities of oxidative stress biomarker enzymes, and restore gene expression levels | The liquid smoke can inhibit oxidative stress by pollutants in planarian animal |
| Gomez JP, Velez JPA, Pinzon MA, Arango JAM, Muriel AP. (78) | Chemical characterization and antiradical properties of pyroligneous acid from a preserved bamboo, Guadua angustifolia Kunth. | Experimental study | Liquid smoke from Guadua angustifolia Kunth (153 kg). Temp 250-280 ºC, 2 hours. | Liquid smoke from Guadua angustifolia Kunth (G. angustifolia) has some phenolic compounds, i.e., 1.96 mg GA g-1 for liquid smoke with borax salt (DPPH activity of 70.98%) and 3.84 mg GA g-1 to liquid smoke without borax salt (DPPH activity of 16.667%) respectively. | Liquid smoke from Guadua angustifolia Kunth (G. angustifolia) has some phenolic compounds with antioxidant activity. |
| Kozowyk PRB, Poulis JA, Langejans GHJ. (13) | Laboratory strength testing of pine wood and birch bark adhesives : A first study of the material properties of pitch. | Experimental study | Tar from pine & birch wood (unknown process) | Tar from pine and birch wood is heated at 150–200 °C for 10, 20, and 30 minutes to become a pitch adhesive. The pitch adhesives, both pine and birch pitch, behave similarly at room temperature and are sensitive to ambient temperature changes. At 0 °C, the pith adhesive is very strong, but at 38 C, it is very weak. | The research results validate previous archaeological adhesive studies that tar from the pyrolysis process could be utilised as an adhesive. |
| Stacey, Rebecca J Dunne, Jul Brunning, S Devièse, T Mortimer, R Ladd, S Parfitt, K Evershed, R Bull, I (15) | Birch bark tar in early Medieval England – Continuity of tradition or technological revival | Experimental study | Birch bark tar from early Medieval sites in England | This research reports new findings of birch bark tar that contains fatty tar as additional material to tar modification. The birch bark tar was from early Medieval archaeological contexts in the UK. It is possible for medicine, or it is associated with a ceramic container used for processing the tar. | Tar material from two early Medieval sites in England has been analyzed. This finding proves that tar from the pyrolysis process has been utilized since ancient times |
| Wang J, Potoroko I, Tsirulnichenko L (50) | Food bioscience wood vinegar and chitosan compound preservatives affect fish balls' stability. | Experiemtal study | The refined liquid smoke from *Pinus koraiensis*wood (unknown process) | The liquid smoke combined with chitosan gave a lower aerobic plate count and pH value than the control group during 15 days of storage. The percentage of free water in the control group was significantly higher than in all treatment groups (0–6 days). The pH value of the treatment group was lower than that of the control group ($p < 0.05$) from 9 to 15 days. The increasing storage time will decrease the trend of hardness, chewability and resilience of fishballs in the treatment groups. | Liquid smoke (1, 1.5 and 2% concentration) and chitosan (0.05, 0.1 and 0.15%) could be used as fishball preservatives in a vacuum bag and minus 4 ºC storage. |

## Lignocellulose, Pyrolysis, and Liquid Smoke

Lignocellulosic biomass is a renewable and affluent resource from plants that mainly consists of cellulose and hemicelluloses (polysaccharides) and Lignin (an aromatic polymer), which has a high potential as biochemical and biofuel sources (7). One of the lignocellulosic biomass utilization techniques is the pyrolysis process. Pyrolysis is the thermal decomposition of biomass matter without oxygen to produce solid and liquid products (charcoal, bio-oil, or wood vinegar) (8). Wood vinegar or liquid smoke (LS) is a liquid from the carbonization/pyrolysis process of waste and lignocellulosic biomass. Rapid depolymerisation establishes liquid smoke and concurrently breaks down hemicellulose, cellulose, lignin, and organic parts. Biopolymers are cracked into smaller molecules by high temperatures and limited water. The smoke from the carbonization process flows into the condenser to become a liquid, i.e. liquid smoke (9). Pyrolysis generally occurs at temperatures above 300°C, lasting 4-7 hours. This process involves various reactions: decomposition, oxidation, polymerization, and condensation. The end product of biomass pyrolysis consists of charcoal (biochar), a gas that can be condensed into liquid smoke/ bio-oil and cannot be condensed (10).

In conventional charcoal production, generally, the condensation compounds are not taken; this is what causes air pollution because the smoke is not condensed. When the smoke is condensed, pyrolysis liquid will be obtained. This product also contains tar, a dark, sticky, and oily material. Tar must be removed from the liquid smoke. It can be done by decantation for several days or weeks until the tar settles and then is separated (11–12).

Based on the findings of archaeologists, it is known that there is a lot of evidence of the use of pyrolytic liquid/tar. It began with using tar from birch bark in the Middle Paleolithic era of Neanderthals (200.000 BC). It is made by thermal processing, where the tar is continuously heated until it produces pitch (further fractionation of tar and more solid). This pitch is used as an adhesive for many purposes, i.e. weapons or tools for hunting (13).

In the Mesolithic period (10000-5500 BC), there was much evidence of lumps of birch bark tar with molds teeth of humans. The tar was used for dental treatment and therapeutic purposes. In the Neolithic period (2000 BC), when human life had begun to know culture and farming, they used tar as an adhesive and a waterproof for ceramic containers. Then the manufacture and utilization were rife in prehistoric and Middle age in Europe. The use of pyrolytic liquids also continues to develop and be practiced by the ancient Egyptians, Chinese, Romans, Greeks, and Balkans, who have made charcoal by carbonizing wood and collecting volatile compounds that can be condensed for mummifying purposes and waterproof wood containers. Archaeological findings in Sweden show that around the eighth century AD, tar was produced in large quantities, around 300 liters per production which were generally used for treating, sealing, and protecting the wood (14–16). Since the early nineteen century, liquid smoke has been applied in agriculture as a soil treatment, pest repellent, and plant growth (17).

## Raw Material Chemistry

History shows that wood from forests was a source of raw material for pyrolysis/carbonization, and its primary production was charcoal and tar as by-products of carbonization. At that time, carbonized smoke was not condensed with a condenser but allowed to escape into the air. The smoke trapped in the wood pile will condense naturally and collect at the bottom of the pit kiln reactor (14). After cooling and harvesting the charcoal, the thick liquid (tar) is collected and used for wood preservation, especially for wooden ships. Furthermore, not only wood as a raw material but also lignocellulosic from agricultural, forestry, and plantation waste, i.e. parts of wood, grain husks, bark, coconut/palm shell, bamboo, and others (18–21).

Generally, the raw liquid smoke materials used contain cellulose, hemicellulose, lignin, and extractive substances at different levels. Wood generally contains 42-45% of cellulose, 28% to 35% of hemicellulose, and 16–33% lignin which are the main components of wood and the main constituent of plant cell walls. At the same time, minor compounds consist of extractives and ash (22).

Looking at the smaller structural units, we find wood's elemental and organic composition. The four main constituents of lignocellulosic are carbon (46.3-51%), oxygen (40.9-46.9%), hydrogen (5.4-6.2%), and nitrogen (0.35-1.69%) which depends on the type of lignocellulosic biomass. These elements are combined in complex molecules, which then combine to form polymers. This polymer provides the structural integrity of the wood. In addition, wood contains a small quantity of inorganic compounds (23–24).

Most wood is composed of cellulose, accounting for almost half of soft and hardwood (40-50%). Cellulose, hemicellulose, and lignin in hardwood are 40-45%, 25-35%, and 16-25%, respectively, while in softwood, they are 40-45%, 25-29%, and 25-30%. A linear polymer with a high molecular weight called cellulose comprises 1.03 nm long cellobiose dimeric units alternately formed from β-D-glucopyranose monomer units. Wood's cellulose is thought to have a degree of polymerization (DP) of around 10,000. The cellulose chain is straight and unbranched. Some cellulose chains are firmly held together by hydrogen bonds (H-bonds) to form microfibrils. Some serve as the main structure of plant cell walls (main structural substances). Found also in nails, lichens, bacteria, algae, and fungi. The purest natural cellulose is found in cotton fibers (± 98% cellulose). Cellulose is the basic material of many products, i.e. paper and rayon fiber/textiles (25–26).

## Hemicellulose

Hemicellulose was originally believed to be an intermediate in cellulose biosynthesis. It is now known that hemicellulose belongs to a heterogeneous group of polysaccharides formed by different cellulose biosynthetic routes. Unlike cellulose which is a homopolysaccharide, hemicellulose is a heteropolysaccharide. Like cellulose, most hemicellulose is a supporting material in the cell wall. Acids relatively easily hydrolyze hemicelluloses to their monomeric components. They consist of several types of sugar (Heteropolysaccharides). It has shorter molecular chains than cellulose (DP=100-200) and short branches of sugar units. Hemicellulose is about 20-30%, easily soluble in water, and serves as support material (27).

Hemicellulose is more reactive, hydrolyzed, and less heat-stable than cellulose and lignin. The surface of the highly polar microfibrils and the low polar lignin matrix are coupled together by hemicellulose. Hardwood has more hemicellulose than softwood, and pentosan content and degree of acetylation are higher (28–29).

The type of sugar in hemicellulose is pentose and hexose. The pentose consists of; xylose, arabynopyranose, and arabinofuranose—hexose: glucose, mannose, and galactose. Hexuronic acid: galacturonic acid, glucuronic, and 4-O-Methyl glucuronic acid. Meanwhile, the deoxy-hexoses are rhamnose and fucose (30–31).

**Lignin**

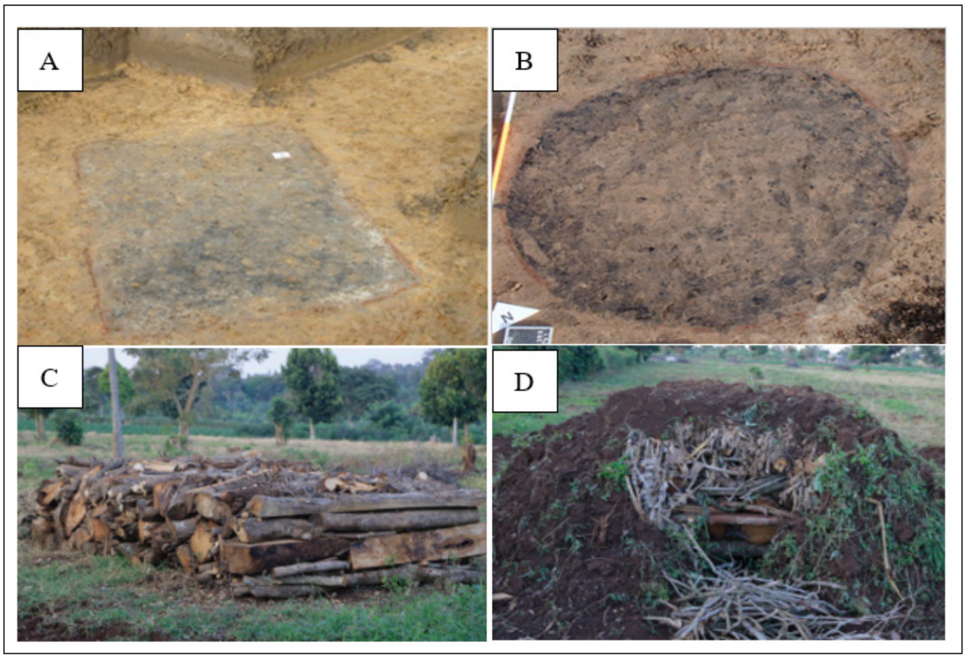
Lignin is a very amorphous phenolic polymer with indefinite molecular weight. Using a free radical mechanism, the lignification process of wood cell walls involves the diffusion of phenylpropane monomer units and polymerization to create a random three-dimensional network. Despite the frequency of various bond types being known, lignin lacks a clear structure due to the random nature of the polymerization activity. The middle lamella region's cells are bound together by lignin, making the cell wall stiff. Despite being relatively inflexible at ambient temperature, lignin goes through a glass transition at about 140°C. Moisture within the cell walls also acts as a plasticizer for the lignin network. The lignin structure is made more accessible by water vapor in the cell wall. Compared to the other polysaccharide components, lignin has a low concentration of OH groups. Syringyl content in hardwood lignin ranges from 20% to 60%, whereas it is relatively low in softwood lignin (25,32–33).

**Production Techniques**

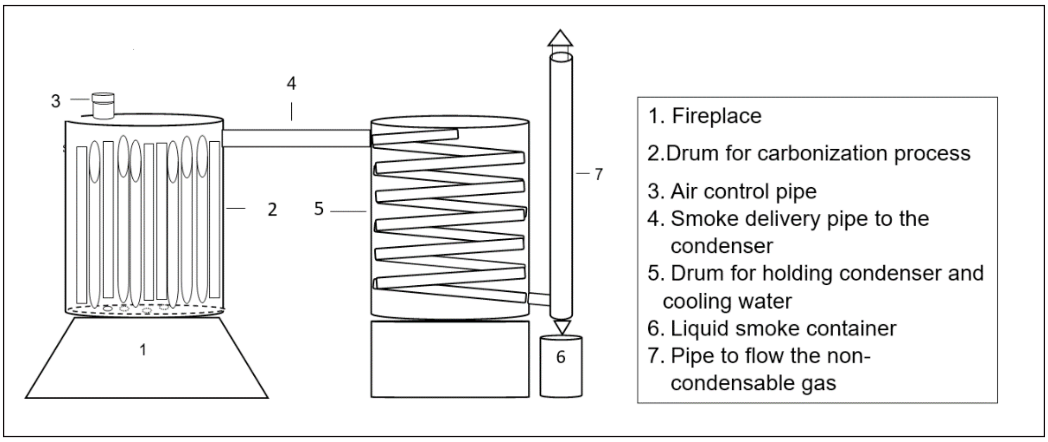
In general, the liquid smoke production through a pyrolysis or carbonization process of lignocellulosic biomass without air occurs at a temperature of 200-500°C. Fast pyrolysis and slow pyrolysis are the two methods of pyrolysis. Slow pyrolysis is a technique of carbonizing lignocellulosic materials using a temperature of 200-500°C and lasts for 5 hours – 8 days, based on the quantity of raw resources and the technique employed. Slow pyrolysis is an easy carbonization technique practiced by the ancient Chinese. The reaction process is a thermal conversion in which lignocellulosic materials are heated slowly in the lack of air to an ending temperature of around 500°C. It is called slow because the contact between raw materials and the heat source occurs slowly and gradually. The raw materials can be small to large with a diameter of 10-20 cm (logs are usually split first). The main products in this process are about 30% charcoal, about 30% bio-oil/ter, and about 35% gas content (9).

Fast pyrolysis is a carbonization process using a 450-900°C temperature. It is called fast because the contact between raw materials and heat sources occurs quickly in 2-10 seconds. In this process, the reactor is preheated to the specified temperature, and the raw materials are fed into the reactor after the temperature is reached. The raw material size should be powder. The main product from the fast pyrolysis technique is bio-oil, which is dark brown to black (9,34–35). Bio-oil can be an alternative substitute for hydrocarbon fuels for industries such as combustion engines, boilers, stationary diesel, and turbines and a substitute for heavy fuel oil, light fuel, and natural gas for various boilers. However, bio-oil cannot substitute for transportation fuels due to its high acid content, oxygen, and viscosity and requires upgrading processes, i.e., catalytic cracking. Bio-oil is an environmentally friendly fuel consisting of lignin derivative, organic compound, acid, and carbonyl (36–37).

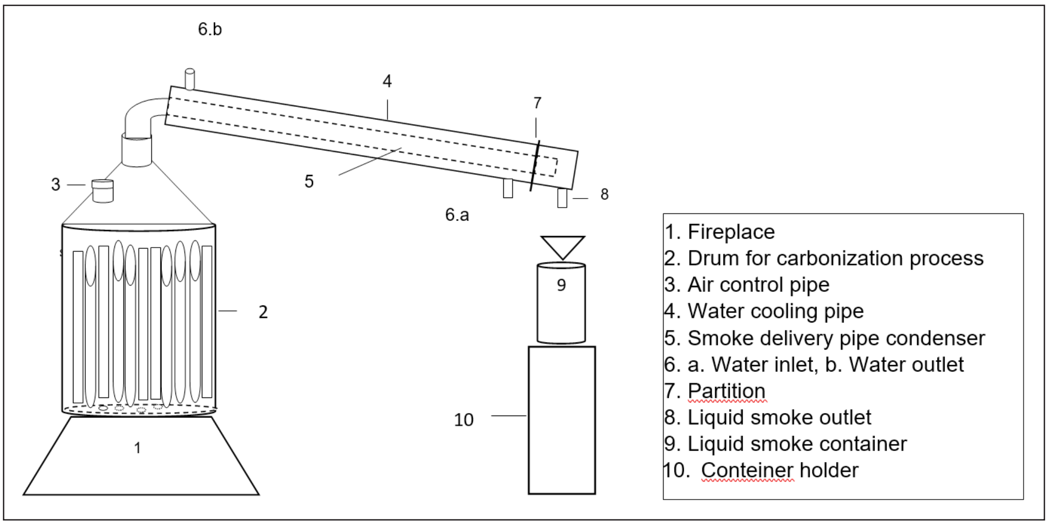
Slow pyrolysis is usually used to produce liquid smoke because the technology is simpler than fast pyrolysis. Liquid smoke can be produced using various reactors: a pit kiln, a brick dome reactor, or a metal reactor such as an old drum, iron, or stainless steel. The pit kiln technique has been used since ancient times. Some archaeologists have found evidence of charcoal and tar production in Belgium, the Netherlands, Sweden, and other areas from 2500 BC to 800-900 AD (14,37). At that time, the pit kiln was used with two production techniques: 1) charcoal production without collecting tar. In this technique, they use rectangular or circular pit kilns and mound kilns (the techniques for stacking wood on the ground (Figure 1) (38–39). 2) The production of charcoal with the collection of tar. In this technique, they made a conical hole, usually in the valley slope, with a tar channel or container at the bottom of the pit (Figure 2).




*Source: Deforce K, Groenewoudt B, Haneca K (38), Nabukalu C, Gieré R (39)*
**Figure 1. Rectangular Pit Kiln (A), Circular Pit Kiln (B), Mound Kiln (C and D)**




*(a)*




*(b)*

*Source: Komarayati S, Wibowo S (40)*
**Figure 2. Drum reactor model 1 *(a)* and model 2 *(b)***

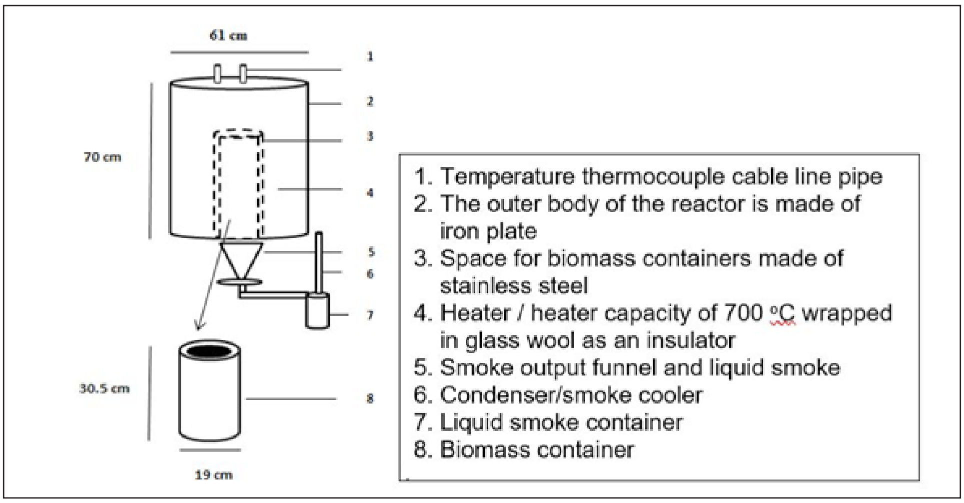
They use pine or conifer wood stacked until it fills the kiln pit, ignited, and covered with litter or clumps, charcoal, and soil to control oxygen. Heat propagation will burn the wood slowly and produce smoke which then condenses to produce liquid smoke and tar, drips down, and enters the channel or tar container (14).

Tar production in Sweden has been carried out since the eighth century AD. Even for radiocarbon products, there are kiln holes made in AD 680–900. However, it won't be easy for now because it requires a suitable location, namely in the forest. At the same time, producing charcoal in forest areas is currently impossible.

The heat source can use electrical energy or a direct fire source, and the raw material capacity can adjust according to the final destination, i.e. for extensive or commercial use or research and development. There are some research and development regarding the production of liquid smoke. Center for Research and Development of forest products, Bogor, Indonesia, in 2015, using a drum reactor to produce liquid smoke from three bamboo species. There are two models of drums reactor; the first is two drums model, the first is a carbonization container, and the second is a spiral condenser container with water. The second reactor is one drums model as a carbonization container, and the condenser uses a straight pipe condenser covered with a larger pipe filled with cooling water (Figure 2). The raw material capacity was around 30-100 kg, with the heat source coming from a fire fed at the bottom of the drum. This drum reactor with a spiral pipe condenser produced a yield of 5-6% liquid smoke and a straight pipe condenser of 24% (40).

Another metal reactor was designed and built at the University of Kentucky, USA, in 2016 and was used at Makerere University in Uganda for liquid smoke production from banana waste in 2017. The reactor has a capacity of 37.6 liters and can reach temperatures of 350-550ºC with an energy source from firewood. The condensation system consists of two pipes for heavy and less dense gases. In this study, there was no information about the yield of liquid smoke obtained from this reactor (41). In 2018, Chulalongkorn University used modification metal kiln with a heat distribution pipe. The reactor has 4710 liters capacity equipped with a condenser. The reactor's temperature can reach 600 ºC with energy from firewood as feed for heating the reactor. They tested 1446 kg of bamboo with 30% moisture content. They found 315 kg of charcoal (21.8%) and 900 L of crude liquid smoke (62.2%) (11). The high yield of liquid smoke is possible because the moisture content of bamboo is relatively high, namely 30%.

Apart from wood, electricity can be used as an energy source for ignition in the reactor, starting from a small scale (only for characterization) to a pilot/small industrial scale. The Research Institute of Forestry New Technology, Beijing, uses small-scale reactors with electrical energy. They carried out pyrolysis temperature stages of 20-150ºC, 150-250ºC, 250-350ºC, and 350-450ºC on 20 g of Chinese fir sawdust (*Cunninghamia lanceolate* (Lamb.) Hook, using a small capacity tube reactor (20-50g) with furnace heating. The reactor is only to determine the chemical characteristics of liquid smoke with limited samples (42)**.** The Research and Development Center for Forest Products Bogor, Indonesia, had a slightly large carbonization reactor (up to 5 kg of material). Designed and built around 1930 and is still operating today. The size of the main reactor is 50x50 cm, but the container is 45 cm high and 20 cm in diameter, or a capacity of around 3-5 kg of wood/biomass. The container is inserted into the furnace with the smoke flow facing down (Figure 3). The reactor can be operated at temperatures up to 500ºC and connected to a glass condenser (43).




*Source: Wibowo S (43)*

**Figure 3. Electrical Reactor (43)**

Dome kilns can be used to produce liquid smoke. In Asam-Asam District, South Kalimantan Province, a dome kiln with a capacity of 50 tons is used to produce charcoal and liquid smoke from ironwood waste. The carbonization process was carried out for 21 days at 400-600ºC. This process obtained charcoal and liquid smoke yields 14% and 0.05%, respectively (18). The yield of liquid smoke from the dome kiln reactor is generally low because the main production dome reactor is charcoal instead of liquid smoke.

In the course of pyrolysis, water is lost from the biomass at about 200ºC, hemicellulose conversion at 200ºC to 355ºC (producing large syn-gas/volatiles, a small amount of tar and char, and liquid smoke), cellulose decomposes at 240ºC to 410ºC (producing syn-gas, liquid smoke, and charcoal), and lignin decomposes at 150ºC to 900ºC (producing liquid smoke/bio-oil and charcoal are produced) (44–46). Wood can burn because the cell wall polymer undergoes hydrolysis reactions (breakdown of water molecules ($H_2O$) into hydrogen cations (H+) and hydroxide anions (OH−), oxidation (removal of electrons by a molecule, atom or ion), dehydration (reduction of water content), and pyrolysis as a result of increasing temperatures and producing volatile and flammable gases. In addition, the carbon (45-50%) and hydrogen (5-6%) content in wood is relatively high (47).

White smoke initially occurs as carbonization starts. Since the water in the biomass evaporates as vapor, the smoke is wet. At this point, the furnace's interior temperature is 300°C, but from the flue, the temperature of the smoke is 80°C. The smoke then returns to its original color of white before changing to a blend of yellowish brown and burning scent that irritates the eyes later. White smoke erupted again, and the odor changed to one fragrant (9).

In general, liquid smoke production techniques are carried out in one step, i.e., after the pyrolysis process (from room temperature to a final temperature of 500ºC). Of the 32 relevant research articles, 25 articles convey the production and application techniques of liquid smoke, all of which use slow pyrolysis techniques using either clay/Iwate reactors, drum reactors, or metal/SS reactors. In addition, some journals do not mention the production techniques carried out in their research, only information on obtaining/purchasing liquid smoke from other parties. Some journals explain the production of liquid smoke using several temperature treatments, namely research on the production of *nyamplung* shell liquid smoke at temperatures of 200, 300, 400, and 500ºC, then palm shells at 340, 360, 380ºC and research on rice hull liquid smoke at 300, 340, 380ºC (20-21,43). However, the review results show that this study used one step of pyrolysis temperature per temperature treatment. This technique produces liquid smoke with generally high levels of phenol and acid due to the accumulation of lignocellulosic degradation from the initial chemical breakdown of lignocellulosic to the final temperature.

In comparison, the production of liquid smoke through temperature stratification has not been done much. There is one journal that informs the pyrolysis temperature stratification technique, where liquid smoke is collected at certain temperature intervals or ranges, i.e. 20 to 150°C, then from 150 to 250°C, from 250 to 350°C, and from 350 to 450°C, all in one time pyrolysis process. The results showed that liquid smoke collected at 20 to 150ºC was the best treatment for the growth of wheat plant seeds compared to others (42). Pyrolysis temperature stratification allows different levels of phenol and acid for various applications. Pyrolysis moderate temperatures (200-300ºC) have lower levels of acids and phenols, so they are safer for plant research applications than high temperatures, which are more suitable for research antimicrobials, herbicides, non-food preservatives, and deodorizers.

**Physics and Chemical Compounds of Liquid Smoke**

Liquid smoke has polar and non-polar compounds due to the decomposition of wood components (cellulose, hemicellulose, lignin, and other substances) in the pyrolysis process. The compound's proportions depend on the species of raw material being pyrolyzed, the temperature process, and the condensation system. Wood carbonisation at 400ºC produces charcoal, acetic acid, tar, methanol, and non-condensable gas, i.e., 33-41%, 3-7%, 11-19%, 1.5-2.5%, and 15-17%, respectively. Acids such as acetic, propionic, butyric, and others are in the liquid smoke portion. Additionally, catechins, guaiacol, 1,2 dimethoxybenzene, and phenol with paramethyl, -ethyl and n-propyl, 0 and m-cresol, 2,4-xylenol, and 2,6-dimethoxy phenol homologs were found in redwood (*Sequoia sempervirens*). The results of research liquid smoke from *nyamplung* shells at temperatures of 200-500ºC were dominated by organic acids, especially acetic acid, ketones (acetone), aldehydes (furfural) and phenolic compounds. The pyrolysis temperature difference of 200, 300, 400, and 500ºC produces a different chemical composition of liquid smoke. The temperature of 200-300ºC liquid smoke from *nyamplung* shells is dominated by acetic acid. At a temperature of 400-500ºC, liquid smoke is dominated by phenolic compounds and organic acids (43).

Liquid smoke consists of 80-90% water from the evaporation of raw materials during the dehydration and pyrolysis processes. A water-soluble chemical compound made up of acids, sugars, ketones, alcohols, and aldehydes produced from the breakdown of carbohydrates is between 10 and 20% of the total weight. Furthermore, phenol, guaiacol, and syringes are derived from lignin degradation. While furfural, furan, levoglucosan, and levoglucosenone are derived from the decomposition of cellulose. Simple organic compounds are converted from waxes, fats, mucilages, terpenoids, and alkaloids. Complex inorganic and metal salts it is usually reduced to ashes. Water is usually miscible with alcohols, ketones, hydroxy aldehydes, acid, and oligomeric lignin-derived components (9).

The liquid smoke's physical properties were analyzed: pH, color, odor, and the presence or absence of tar deposits. pH is the level of acidity of liquid smoke; the lower the pH, the higher the acidity level of liquid smoke caused by organic acids, for example, acetic acid, propionic acid, and butyric acid. Generally, the pH of liquid smoke is between 1.3-3.8 (43,48). The color of liquid smoke varies from black, blackish brown, light brown, and reddish yellow to clear yellow. Liquid smoke from carbonization (crude) is generally blackish–reddish brown. When redistillation occurs, the color can be brownish-yellow to clear-yellow. The smell of liquid smoke is quite strong, caused by the compounds present in the liquid smoke, especially phenol, and generally, the tar that settles at the bottom of the container. Tar can be separated by liquid smoke decantation for some weeks to a few months or a re-distillation technique of crude liquid smoke (19,49). The decantation process does not require money and equipment but requires quite a long time. Meanwhile, re-distillation does not take long but requires additional costs for heat energy and distillation equipment and the loss or damage of several chemical components.

## Liquid Smoke Application

### Liquid Smoke for Food Preservatives

The chemical compounds in liquid smoke, it makes have various benefits. Liquid smoke can be used as a preservative for meat, meatballs, noodles, and fish. Research on the benefits of palm kernel shell's liquid smoke as a fish ball preservative was conducted at Syiah Kuala University, Indonesia, in 2018. They re-distillation liquid smoke from temperatures 340ºC-380ºC twice to obtain grade-1. Then liquid smoke grade-1 was diluted to 1, 2, and 3% concentration and used as fish ball preservatives. They found that a 3% concentration of grade-1 liquid smoke from 380ºC has the lowest of total volatile base at twenty hours of observation (20).

Furthermore, research was done on the potential of mixed rice husk liquid smoke (liquid smoke redistillation into food grade) and chitosan as curing beef. Using liquid smoke with a concentration of 3% and 0.5 -1.5% chitosan for marinating beef has succeeded in maintaining the freshness of beef (21). In addition to beef, a mixture of liquid smoke and chitosan has been successfully applied as a preservative for fish balls in vacuum storage. After fifteen days, the treated fish balls produced meatballs with a lower total plate count and TVB than the control (50).

### Liquid Smoke for Plants

Liquid smoke has a long history of use, as was previously mentioned. One example is Japan, where liquid wood smoke has been applied as fertilizer and plant growth in agricultural land since the early nineteenth century. Here are some studies showing the effectiveness of liquid smoke for plants. A study has been carried out on the impact of liquid smoke and organic chemical mixture on the growth and yield of rapeseed plants with liquid smoke and adding other chemicals organic in the treatment, i.e., control (water), liquid smoke on 0.25% concentration, liquid smoke mixed gibberellin (A), gluconate (B) and melatonin (C). They conducted research for two years to know the growth effect on rapeseed. The results show that the number of pods, grain yield, and leaf width of the rapeseed were increased compared to the control. However, the A, B, and C treatments increased grain yield compared to the 0.25% liquid smoke treatment. The application of liquid smoke reduced the attack of white mold and downy mildew, especially for liquid smoke mixed mentioned in treatment (C). It also succeeded in increasing the tolerance of rapeseed plants at cold temperatures (51).

Research on tomato plant fertilization was conducted at Khon Kaen University Thailand in 2013. A mixture of liquid smoke from eucalyptus wood and fermented bio extracts (from plants or animal residues) was used as fertilizer. Soil and foliar spray applications are carried out after the plants are 30 days old from sowing the seeds with control and nine treatment. Implementation of liquid smoke and FB either by oneself or combined treatment indicated a slight increase in the dry weight of the plant, the quantity of fruit, and the weight of fruit (fresh and dry). Still, it significantly increased the total dissolved solution of tomato fruit. Liquid smoke and FB extracts have the same effect on tomato yield and growth. Yet, the combined application has a supplement effect on tomato growth. Liquid smoke and FB extracts can be applied as foliar or soil sprays (52).

Khon Kaen University Thailand 2014 continued the research using eucalyptus wood liquid smoke (0.33%) used for foliar application at first 30 days after planting to 10 days before maturity, using 15-day intervals. After cropping, the plots incorporating manure combined with applying liquid smoke showed increasing soil potassium, nitrogen, and phosphor content. Applying liquid smoke mixed with manure produced the most significant grain yield (2,404 kg $ha^{-1}$) due to increased panicles per hill (53).

Furthermore, it has been investigated to use liquid smoke as a substitute for $HNO_3$ to adjust nutrient solutions pH in lettuce hydroponics. Growth rates, photosynthesis, and absorption of minerals and water were poor in the growth of lettuce in a solution of nutrients with 1 ml of $L^{-1}$ liquid smoke. However, the lettuce growth in a solution of 0.25 ml $L^{-1}$ liquid smoke did not significantly differ from the control treatment. Therefore, a 0.25 ml $L^{-1}$ concentration of liquid smoke was adequate to maintain the hydroponic solution pH within the optimal scale for lettuce growth (54).

Liquid smoke has also been utilized as a levulinic acid source to increase the 5-amino levulinic content in unsterile latex rubber sheet wastewater. As a result, adding liquid smoke in the concentration of 0.63%-1.25% remarkably increased the 5-amino levulinic by 3 to 4 times compared to the control. It can reduce amino levulinic production costs by about 31 times with liquid smoke (55). Liquid smoke has also been used for seed priming. The effect of liquid smoke from white pine biomass on seed priming of tomato seeds has been investigated. Liquid smoke concentrations of 0.08%, 0.11%, 0.17%, 0.33%, 0.5%, 1%, and 2% were used to determine the germination and growth of tomato seedlings in growing media containing aluminium chloride/Al. It was found that seed priming with 2% liquid smoke significantly reduced aluminium-induced oxidative stress and increased germination and seed growth indices, increased length and hypocotyl surface area, root volume, and fresh seedling weight (56).

Another research uses liquid smoke and charcoal (biochar) from corncobs and rice straws waste on the growth of cayenne pepper. The concentration of liquid smoke consists of 0%, 4%, 6%, and 8%, while biochar consists of 0 g, 10 g, 20 g, and 30 g. It was found that the combination of 6% liquid smoke concentration and 20 g biochar produced more leaves, while the 8% liquid smoke concentration and 30 g biochar affected plant height, fruit weight, and the number of leaves and fruit (57).

Not all liquid smoke studies yield significant results on plant germination and growth. Research on the addition of liquid smoke from wood waste with different dilutions (500-500.000 times) or concentrations of liquid smoke between 0.2%-0.0002% did not give significant results on cucumber germination and growth. However, adding dilution liquid smoke 1000 times (0.01% concentration) increased the cucumber plant's 5.92% dry biomass and 20.9% root length (58).

Research on the effect of poplar (*Populus trichocarpa*) liquid smoke on rapeseed (*Brassica napus* L.) germination was conducted in Shandong, China 2018. The results showed that 1% liquid smoke had the most significant inhibitory impact on rapeseed germination. Raw liquid smoke and distilled liquid smoke at 98 – 130°C valuably inhibited seed germination. However, distilled liquid smoke at 0-98ºC increased shoot length (58.4%) and root length (31.7%). These advantageous outcomes can be linked to more incredible plant growth, higher soil fertility, and increased nutrient availability. For fostering plant development and boosting crop yields, distilled liquid smoke (0-98ºC) may be an expectant soil additive (59).

The performance of liquid smoke and bio-charcoal for agricultural plants was also studied at the Ocean University of China, Qingdao, China, in 2019. For five hours, liquid smoke and biochar from Poplar waste stem were carbonized at 500 °C. They chose red pepper and tomato to determine the response to the supplemental liquid smoke and biochar (separate and co-application) on seed germination using a pot for 30 days. The result shows that adding LS did not affect the germination speed but increased the length of roots and shoots at low doses (0.002% and 0.02%). In addition, LS individually boosted the root growth of red paper but shared apps with biochar show low effects. Unlike tomatoes, LS individually had little impact on development, while biochar individually facilitated seed and root growth and biomass production. The shared application of LS and biochar remarkably increase the tomatoes' volume and root length (60).

Liquid smoke was also studied for its effect on wheat root growth in liquid smoke-soaked seeds and controls under drought stress conditions. The results of their research showed that there was an increase in the activity of antioxidants. At the same time, wheat roots in drought stress had lower amounts of reactive oxygen species and malonaldehyde than the control. This research shows that liquid smoke can increase plant tolerance to drought stress (17).

Not only for plant germination and growth, but liquid smoke also controls weeds. A study conducted by the University of Alcalá, Madrid, Spain, in 2020 tried to investigate the characteristics of the chemical composition of liquid smoke from poplar wood, pine wood, pruning litter, and forest waste through fast pyrolysis as a herbicidal weed. The liquid smoke contains over 200 compounds and is dominated by acetic acid, acetone, and acetaldehyde. Liquid smoke is established to be potent as a herbicide against weeds at concentrations of 50-100% (61).

**Liquid Smoke for Antioxidant and Antimicrobes**

Liquid smoke is not only used for plants but is also helpful as an antimicrobial against bacteria, mold, and viruses. The following is research related to this topic. Phenol is an antioxidant substance that has been utilized widely in the world. The Research of antioxidant compounds in pine wood (Pine tabulaeformis Carr) liquid smoke was conducted at the Shenyang University of Chemical Technology, Shenyang, China, in 2018. A total of 48 organic compounds were identified. The results of liquid smoke isolation showed that the highest total phenol was found in the dichloromethane extract. Seven types of phenol were isolated from LS, and all produced vigorous antioxidant activity on AzBTS, DPPH, and FRAP (62).

Liquid smoke as an antiviral has been studied using liquid smoke from oak wood, mosso bamboo, and conifer wood to disinfect the EMCV virus. There are 25 phenolic constituents in liquid smoke, while Moso bamboo has higher phenolic than oak and conifer wood. The rich compounds in the liquid smoke studied were 2- methoxy 4-ethylphenol, 2-methoxy phenol, and 2-methoxy 4-ethylphenol. The total phenolic hydroxyl groups substantially influence antiviral activity, and catechol and its derivatives have a more substantial viral inhibitory impact. Methoxylated phenol compounds are less active than methylated phenol (2 methyl phenol and 2-methoxy phenol). A crucial factor in the viral inhibitory effect is the relative location of the functional groups (2,6 dimethoxyphenol and 3,4 dimethoxyphenol) (63).

The research was continued by using liquid smoke from Japanese larch wood (Larix kaempferi) for antiviral activity on EMCV. They found the main compound with antiviral activity, i.e., 4-methylcatechole, 4-ethylcatechole, 3- methylcatechole, 3-methoxycatechole, and 2-methyl 1,4 benzenediol. The structure and position of the phenolic substituent groups attached to the aromatic backbone affect viral inhibition. In the paraposition connected to a hydroxyl group, methyl and ethyl substitutions increased the antiviral activity (64).

Fruit tree wood waste can produce liquid smoke which has the potential as an antimicrobial. Research has proven that liquid smoke from longan wood waste can be against bacteria and fungal in vitro tests. It is confirmed that longan liquid smoke indicates antibacterial activity for fourteen bacteria, but only one fungus (*Candida albicans*) is inhibited. GCMS analysis shows the detection of oleic acid, palmitic acid, and myristic acid, which dominate longan liquid smoke (65).

A study mixes three types of wood in one pyrolysis reactor to produce liquid smoke. This research investigates the effect of liquid smoke from a mixture of three softwood, i.e., a combination of fir + spruce (20%) and pine (80%), for antimicrobial activity. Two pH conditions for liquid smoke, namely acidic pH (3.7) and neutral pH (7), are produced by adding 12 M NaOH solution to liquid smoke until a neutral pH is obtained. The result shows that neutralized liquid smoke increased activity against bacteria (*E.Coli, E aerogenes, Pseudomonas sp, and E. faecalis*) compared to acidic liquid smoke (pH 3.7). Conversely, acidic liquid smoke gave higher inhibition to fungi (*Trametes versicolor, Aspergillus fumigatus,* and *A.niger*) (66).

**Liquid Smoke for Animals and Insects**

Liquid smoke not only inhibits microorganisms but is also used for insect control and animals purpose. These results were obtained from research on the potential of liquid smoke from some lignocellulosic waste (pine bark and residue, straw, and salix coppice) for insect repellent, insecticide, and herbicide. They compared slow and hydrothermal carbonization techniques in producing liquid smoke and their characteristics. The result found that salix coppice liquid smoke from slow carbonization gave the most effective snail repellent compared to others. Meanwhile, liquid smoke from the hydrothermal carbonization technique is less effective in pesticidal or repellent activities (67).

Liquid smoke is proven as an antibiotic in animals. A study has used bamboo liquid smoke as an alternative to antibiotics in weaning piglets' diets on growth and the fecal bacterial community. It discovered 34 chemical peaks in bamboo liquid smoke in the acetate ether extract, where phenol, ketone, and furfural are the three main groups in liquid smoke. They use bamboo liquid smoke at 0% (control), 0.2, 0.4, and 0.8%, and antibiotics. The findings demonstrated that bamboo liquid smoke in the feed affected the piglets' fecal bacterial population and had potential application as an additive in livestock production in place of antibiotics (68).

The house fly is a pest of home and farm that carries pathogens such as *E. Coli*, Salmonella, and others. Liquid smoke can be used to control house flies. A study has been conducted to investigate liquid smoke from wood waste on flies toxicity tests using contact application and feeding methods. They studied the activity of liquid smoke at 10, 15, 20, 25, and 30% for larvicidal house flies. They proved that the feeding application gave a higher larvacidal effect than the topical method. The liquid smoke in high concentrations (> 10%) with exposure time will increase the mortality of fly larvae, but at 10%, no mortality is found (69). Another technique for using liquid smoke is to impregnate the liquid smoke with wood as an antifungal. Duzce University, in Turkey, has studied the impregnation of liquid smoke of oakwood (*Quercus petraea*) on pine and oriental beech wood. Oakwood liquid smoke concentration consists of 1%, 5%, 3%, and 6%. After impregnation, the wood samples were tested on fungi, molds, and larvae. The research found that liquid smoke can be used as an antifungal on white-rot and brow-rot, antimold on *A. niger*, *P.brevicompactum*, and *T.harzianum* as well as anti larvae on *Hyloptrupes bajulus* (70).

Liquid smoke positively responded to nematode attack as evidenced by research on the biological effects of king nut shell liquid smoke on the nematode *Caenorhabditis elegant* growth. They found that liquid smoke can save the destructive impact on apoptotic cells and is comparable to other antioxidants, i.e., L-ascorbic acid. So liquid smoke will be an alternative substitute for chemical antioxidants in foods (71). Liquid smoke can also be mixed with activated charcoal to protect piglets from diarrhea. They found that a mixture of activated charcoal and liquid smoke in the proportion of eight g to two mL per kilogram of pig feed successfully prevented diarrhea in baby pigs compared to the control treatment (72).

Liquid smoke is also used to control wood rot, fungi, and termites. The research of fungus and termite used liquid smoke from laban wood at a carbonization temperature of 350, 400, and 450ºC. *Trametes* sp (white rot) and *Fomitopsis* sp (brown rot) were used as fungal tests. They found that a higher temperature of liquid smoke (450 ºC) gives more fungal growth inhibition than a lower temperature (400 and 350 ºC). The only 3% liquid smoke concentration to make a 100% mortality for *Reticulitermes speratus* termite, but needs 10% liquid smoke concentration for mortality of *Coptotermes formosanus*. It is proved that below 10% liquid smoke can expel termites (73).

Interesting research on liquid smoke to mitigate emissions from animal waste was carried out at Tarim University, China, in 2018. They used liquid smoke from cotton stalks to mitigate methane and carbon dioxide emissions in composting livestock manure. The experiment consisted of control and treatment by adding 0.5%, 1.7%, and 3% liquid smoke to the compost mixture. The results after eleven weeks showed that the addition of liquid smoke increased the temperature and significantly decreased the composting time to only ten days. About 3% concentration of liquid smoke reduces methane and carbon dioxide emissions (74).

In another study, liquid smoke reduced fatty acids in chicken eggs. The research utilized liquid smoke peel of *Ziziphus jujuba* Mill seed as a chicken feed supplement to reduce the ratio of omega-6:omega-3 fatty acids in chicken eggs. The liquid smoke concentration of 0.1%, 0.2% to 0.5%, and control were given to chickens for fifty days. The results showed that the 0.2% liquid smoke concentration resulted in a lower omega-6 : omega-3 ratio than the other treatments and had a higher egg yolk content than the control. So the concentration of 0.2% liquid smoke in the feed is enough to give significant results (75).

Liquid smoke is not only produced from one type of wood but a mixture of several types of wood (mixed wood). As did the Shandong University of Technology, China. They investigated hybrid wood waste liquid smoke on oxidative stress in planarians, lipid peroxidation, antioxidant enzyme activity, and mRNA induced by organic pollutants. The treatment consisted of control, organic contaminants with a concentration of 0.5%, liquid smoke with a concentration of 0.1% + 0.5% organic pollutants, and liquid smoke with a concentration of 0.083% + 0.5% organic pollutants. The results showed that adding liquid smoke reduced malondialdehyde levels, increased the activity of oxidative stress biomarker enzymes, and restored gene expression levels. Our results show that a 0.1% concentration of liquid smoke protects against oxidative damage due to pollutants (76).

Liquid smoke's ability to preserve food, plant growth, antimicrobial, and additive in animal feed is due to its compound content, especially phenol and acetic acid. Phenol is a compound that has antimicrobial activity against pathogens and putrefactive organisms, antioxidants, and smoke odors (77–78). Acetic acid compounds have been used since 6000 years ago to treat wound disinfection and antiseptic. Several studies have also proven the ability of acetic acid as an antimicrobial. The findings revealed that acetic acid could provide an anti-bacterial effect. Acetic acid gave a high zone of inhibition against gram-positive pathogens, i.e., *Staphylococcus aureus, S. uberis*, *S.epidermis, and Bacillus cereus. Also, it was for* gram negatives such as *Acinetobacter baumannii, Pseudomonas aeruginosa*, and *P. vulgaris* but less inhibition for *Escherichia coli* (79–81).

Also, phenol is a compound that forms the specific aroma of smoked products, such as the smell of burning, especially the types of phenol guaiacol, eugenol and syringol. Furan, lactone, and carbonyl compounds can give rise to the characteristic smoke flavor of food ingredients. Lactone is an important minor compound in liquid smoke. For example, butyrolactone gives sweet, grilled flavor to foods (82).

From a literature review, liquid smoke is divided into two groups, namely 1) as an antimicrobial, anti-insect, or herbicide. and 2) as a plant growth agent. In the first group, liquid smoke generally uses high concentrations between 5 and 50%, even up to 100%. High concentrations use because the target of liquid smoke is to inhibit or kill microbes, fungi, and insects. In the second group, namely for plant growth, the liquid smoke used is generally a low concentration of 0.001% to 3%. High concentrations or errors in diluting liquid smoke will cause the plants to become poisoned and die.

The literature review results also show that commercial liquid smoke production occurs in one production stage. Namely, the collection of liquid smoke is carried out starting from the initial temperature of dripping liquid smoke (100-120ºC) to the final temperature of the carbonization treatment (400-500ºC). There are also studies on producing liquid smoke by treating it at 250ºC, compared to a carbonization temperature of 300 ºC or 400 ºC. Research on producing liquid smoke using temperature stratification techniques has not been widely carried out, especially for its application to microbes and plants. The temperature stratification technique is the collection of liquid smoke carried out at a certain temperature in stages, for example, taken at a temperature of 200ºC, then grabbed again at a temperature of 300ºC, and also at a temperature of 400 or 500ºC. This technique is expected to produce liquid smoke products with different phenol and acetic acid levels to enable various applications. For example, liquid smoke is used at a temperature of 200-250ºC for plant growth, while 400-500ºC is used for antimicrobials, insecticides, or herbicides.

Based on the description of the review, it is known that liquid smoke consists of three grades. Grade three is crude liquid smoke, liquid from smoke condensation. Grade two is liquid from crude liquid smoke, which is re-distilled, and grade one is liquid from the re-distillation of grade two liquid smoke. Research on the utilization of liquid smoke for food preservation is grade one liquid smoke (for preserving noodles, meatballs, and meat) and grade two for fish or meat with smoke odor. In contrast, research on using liquid smoke for plants, antimicrobials, wood preservation, and rubber coagulants can use grade three liquid smoke separated from tar or grade two. Research on liquid smoke for antimicrobials, insect repellants, and herbicides uses concentrations between 5-50% and even up to 100% (61,67).

Further research on food preservatives made from meat or fish using grade-1 liquid smoke in a low concentration of 1-3% (20,21), while studies on plants use low concentrations of only 0.01-4% (51–54,56,83). This condition shows a significant effect on the levels of chemical components in the two concentration conditions. To inhibit or kill microbes requires high levels of phenols and acids, which can damage membranes and microbial metabolism. In contrast, applying high phenol and acid in plants will cause leaf phytotoxicity and cause plant death.

**Future Potential**

Using natural chemicals is a serious concern as an effort to preserve natural resources from employing synthetic chemicals. Liquid smoke is a natural source from the biomass carbonization process, and it has been known and used for thousands of years for the needs and welfare of humankind. It starts from the evidence of archaeological discoveries on the use of adhesives for gun handles and coatings for wooden ships to scientific research that proves the benefits of liquid smoke for plant growth, food preservation, natural pesticides, antivirals, and antimicrobials, weed herbicide, sterile agent. As organic agriculture becomes more popular worldwide, the need for liquid smoke could increase. This demand is caused by concerns about synthetic fertilizers and pesticides that harm the environment. These conditions provide promising opportunities for liquid smoke producers in the future years.

In 2021, the value of the world market for wood vinegar was $5.15 million. In ten years, it is forecast to gain 9.7 million dollars or get compounded annual growth rate (CAGR) of 7.3% (84). Asia Pacific is the highest contributor to liquid smoke, with a CAGR of 7.9%. China, Japan, Indonesia, Philippines, and Malaysia produce countries that influence the liquid smoke market in the Asia Pacific. In second place are the Middle East, Africa, and Latin America, with a CAGR of 7.5%, and third place is North America, while Europe is the liquid smoke market still growing. However, from the search results, data on the amount of liquid smoke production, especially in Indonesia, regionally or nationally, has not yet been recorded in the Indonesian Central Bureau of Statistics. One of the large companies that produce liquid smoke is PT. Global Daerub Industry in Palembang with a production capacity of 1500 -3000 tons per year. Production for domestic use and export to Thailand and Pantai Gading (85)

CV Riko Jaya in Jakarta has a production capacity of up to 3000-3600 tons per year for domestic needs and exports to Thailand, Taiwan, Singapore, and

Malaysia (86). A liquid smoke factory in Aceh Province named ADF Terapan Beunyot with a production capacity of around 140 tons per year, then CV. Prima Rosandries in East Java with a production of 20.8-31.2 tons per year (87). In addition, there are also micro, small, and medium enterprises (MSMEs), home industries, or farmer groups such as the Dewi Sri Farmer Women's Group in Cianjur, West Java, and the Village Women's Fellowship Foundation in Toraja (88).

The problem of the liquid smoke market, especially in Indonesia, is the lack of public understanding of the importance of renewability and environmental safety. Besides that, the belief that synthetic chemicals are more productive, they are cheap and easy to buy. So generally, large producers use marketing strategies by forming agents and retail sales in several big cities, or directly to the target, for example, farms, markets, and farmers, accompanied by education and application demonstrations. For this reason, the government's role is to assist in developing and marketing liquid smoke, considering the enormous potential of lignocellulosic sources in Indonesia. The lignocellulosic waste from the forestry sector contributes 15.4 million tons per year, and from the plantation sector, especially oil palm, around 2-5 million tons yearly (89–90). Besides that, there is a need to educate the public about renewable sources of raw materials and save the environment from pollution by synthetic chemicals. Making liquid smoke as one of the waste handlers not only helps in handling environmental pollution but also opens new jobs, opens the economy, and can become a source of foreign exchange if it becomes an export material.

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## CONCLUSION

Liquid smoke/pyrolignous acid has been used in various fields since thousands of years ago. Starting from wood lignocellulosic materials, then developed in all types of lignocellulosic. The pyrolysis/carbonization process into charcoal and liquid smoke helps to handle lignocellulosic waste from agriculture, forestry, plantations, and households. There are three models of reactors/carbonization kilns/pyrolysis methods for producing liquid smoke; pit kilns, clay/brick kilns, and metal kilns. The highest yields are generally obtained from metal kilns using tubing condensers. Liquid smoke began as an adhesive for gun handles, sealing and protecting the wood, especially for wooden ships. Then since the early nineteen century, liquid smoke has been applied in agriculture as a soil treatment, pest repellent, plant growth, pesticide, antimicrobial, rubber coagulant/ deodorizer, and antioxidant for health. In general, research on liquid smoke is produced using pyrolysis on a one-stage temperature technique (all liquid smoke is collected at the final temperature of the process). While the pyrolysis temperature stratification technique (liquid smoke is collected two to three times during the pyrolysis process), little has been done. So that there are still quite a lot of research opportunities as a diversification of liquid smoke production, where liquid smoke collected at moderate temperature (200 or 300ºC) is used for research on plant growth, while the collection of high-temperature (350, 400, or 550ºC) liquid smoke is for research on antimicrobials activity, anti-termite, herbicides, and wood preservatives.

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