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Liquid Smoke Derived from Sago Processing Solid Waste: Organic Compound Composition and Its Application for Ironwood (*Intsia bijuga*) Seedlings

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ABSTRACT

*Liquid smoke derived from sago processing solid waste can be utilized in various applications, depending on the raw materials and pyrolysis conditions. This study aimed to identify the chemical compounds present in liquid smoke from sago processing waste and to evaluate their effects on the growth of ironwood (*Intsia bijuga*) seedlings. Liquid smoke was produced through a slow pyrolysis process with an average temperature increase of 1.5–1.8 °C/min. Gas chromatography–mass spectrometry (GC–MS) analysis was used to determine the chemical composition of the liquid smoke. The liquid smoke was applied to ironwood seedlings using three treatments: without liquid smoke (AC 0), a mixture of liquid smoke and water at a ratio of 1:20 (AC 1), and 1:200 (AC 2). Observations focused on seedling height, stem diameter, and number of leaves. The results showed that liquid smoke from sago processing waste contained various organic compounds, including acids, ketones, phenolics, furans, ethers, and other related compounds, with acetic acid being the dominant component. However, the application of liquid smoke did not significantly affect the growth parameters of ironwood seedlings.*

1. INTRODUCTION

Pyrolysis is a thermal conversion method for biomass that the primary aims to produce charcoal. In addition to charcoal as a solid product, gaseous and liquid phase products called bio-oil or liquid smoke are also produced. Gaseous phase products can be separated into non-condensable substances or syngas (H_2O, CH_4, H_2, CO_2, CO) and condensable substances including tar and pyroligneous acid (Zhu *et al*., 2021). Pyroligneous acid is commonly known as liquid smoke, defined as an organic liquid produced from the condensation process of biomass combustion smoke such as wood and non-wood (e.g., bamboo, palm oil, etc.) in a pyrolysis reactor with little or no oxygen (O_2) (Shen *et al*., 2020; Putri *et al.*, 2022). This liquid consists of 80–90% water and contains organic compounds consisting of >200 types of polar and non-polar chemical compounds (Theapparat *et al*., 2018). These organic compounds include organic acids, alkanes, phenolic compounds, alcohols and esters, and acetic acid, with a content of up to ±50% (Grewal *et al*., 2018). The high acetic acid content causes liquid smoke to be often referred to as wood vinegar.

Liquid smoke is beneficial for plant growth because it contains phenolic compounds, aldehydes, ketones, organic acids, alcohols, and esters (Koraag *et al*., 2020). According to Iacomino *et al*. (2024), liquid smoke can function as a phytotoxic agent at high concentrations and, when diluted, increases root growth. Liquid smoke can also be used as a prospective soil amendment, thereby improving soil improvement and plant growth (Luo *et al*., 2019). As a planting medium, the soil can be improved with liquid smoke, which allows for binding between the liquid smoke and soil heavy metals that are inhibitors of plant growth (Ju *et al*., 2021). In addition, liquid smoke can have a positive effect on the number and activity of biological factors (microorganisms) in the soil in general (Koç *et al*., 2019). Microbes are able to increase the availability of nutrients in the soil through the decomposition of organic matter, N fixation, and mobilization of P and K (Rashid *et al*., 2016). This organic matter is converted into nutrient forms available to plant, such as ionic species such as ammonium, nitrate, and phosphate (Jacoby *et al*., 2017). In nutrient-poor soils, increased microbial activity can indirectly enhance plant growth. Therefore, the use of large-scale soil media in nurseries can be combined with the use of liquid smoke.

Liquid smoke is an environmentally friendly and potentially beneficial byproduct of charcoal production. This is because the liquid smoke yield is relatively high, around 30%, so liquid smoke production can reduce the amount of smoke emitted into the air, which can cause environmental pollution (Oramahi *et al*., 2021). Liquid smoke yield is influenced by pyrolysis temperature and wood particle size (Oramahi *et al*., 2020). Slow pyrolysis at high temperatures produces a higher liquid smoke yield than low-temperature pyrolysis (Crespo *et al*., 2017). Larger wood particles in slow pyrolysis produce a higher liquid smoke yield than smaller particles (Oramahi *et al*., 2022). Liquid smoke from monocotyledonous plants tends to have a higher yield than that from dicotyledonous plants (Bhuyan *et al*., 2022; Oramahi *et al*., 2020).

Sago palm is monocotyledonous plant commonly found in East part of Indonesia. Processing sago palms can produce sago flour and sago waste. Solid waste from sago processing is typically used as animal feed, mulch, firewood, and as fencing for gardens. Previous research has utilized solid waste from sago processing as a raw material for charcoal and activated carbon. Through a carbonization process and mixing with sago flour adhesive, solid waste from sago processing can be converted into charcoal briquettes for alternative energy sources (Gurusinga *et al*., 2023). Furthermore, through carbonization and activation processes, solid waste from sago processing can be converted into activated carbon, which can be used as an adsorbent (Siruru *et al*., 2018). However, the chemical components and benefits of the liquid smoke product are unknown. Liquid smoke from solid waste from sago processing has different characteristics from other liquid smokes because the characteristics of liquid smoke are influenced by the type of raw material and pyrolysis technique (Kizza *et al*., 2019; de Medeiros *et al*., 2019; Xu *et al*., 2022). Furthermore, research has not yet focused on the application of liquid smoke to growing media. Therefore, this study aimed to determine the content and composition of compounds in liquid smoke from sago processing waste through slow pyrolysis and its application to the seedling process of ironwood (*Intsia bijuga*).

2. MATERIALS AND METHODS

This study was conducted over a 10-month period, from February 2024 to February 2025. The production of liquid smoke from solid sago processing waste was carried out at the Forest Products Research and Development Center Laboratory, Ministry of Environment and Forestry, Bogor. Gas chromatography–mass spectrometry (GC–MS) analysis of the liquid smoke was performed at the National Research and Innovation Agency (BRIN) Laboratory, Cibinong, Bogor Regency. The production and observation of ironwood seedlings were conducted in Batumeja Village, Sirimau District, Ambon.

2.1. Materials and Equipment

The materials used in this study included solid sago processing waste, ironwood (*Intsia* sp.) seeds, liquid smoke, red soil, well water, and polybags. The equipment used consisted of an electric charring furnace equipped with a condensation system, a Shimadzu GCMS-QP2010 Ultra, a digital pH meter, calipers, and a plastic ruler.

2.2. Research Procedure

2.2.1. Liquid Smoke Production

The raw material used for solid waste from sago processing is the outer part of the trunk or bark of the sago tree, or the peripheral parts. This solid waste was dried in the sun to a constant weight with a moisture content of ±14%. It was then cut into pieces to fit the size of the furnace or pyrolyzer (Figure 1). The solid sago waste was heated using a slow pyrolysis method in an electric furnace equipped with a smoke condensation system. The raw material was heated until the furnace reaches 400 °C at a heating rate of 1.5–1.8 °C/min. Once the furnace reached 400 °C, the electricity to the furnace was turned off. It took 4 h to reach 400 °C. The resulting smoke was passed through a glass cooling device containing circulating cold water, which condensed and was collected in a glass flask.

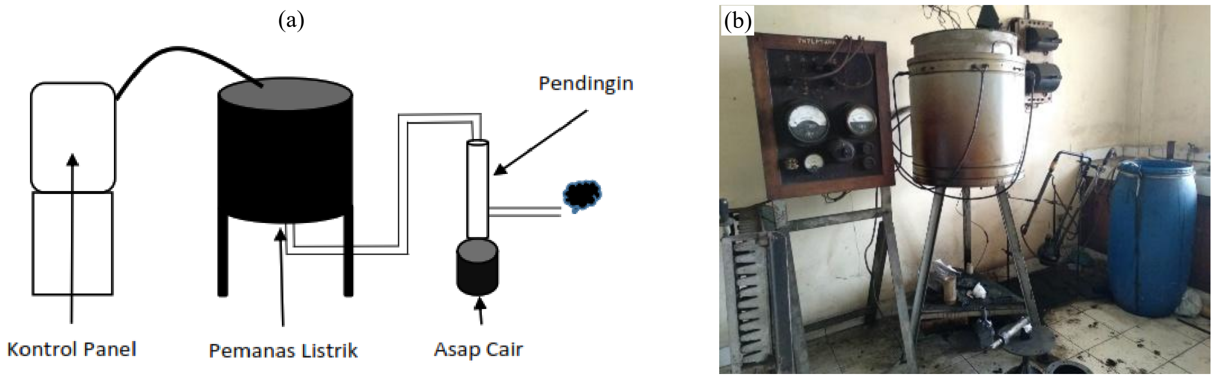

Figure 1. Research apparatus: (a) Schematic diagram, and (b) Real arrangement

2.2.2. Analysis of Organic Compound Composition of Liquid Smoke

Analysis of organic compounds in liquid smoke from sago processing solid waste was conducted using GCMS with a Shimadzu GCMS-QP2010 Ultra instrument. The analysis was conducted for 60 min, with high-purity helium gas flowing through the column at a flow rate of 0.61 mL/min and a total flow rate of 4.2 mL. The injector temperature was set at 250 °C, and the oven temperature was programmed to start at 50 °C, then increase at a rate of 5 °C/min to a final temperature of 280 °C, and maintained for 13 min. Compounds were identified based on retention times and comparison of mass spectrometry data with mass spectral library (NIST) data. Relative peak areas were used to quantify compound content (Dilla *et al*., 2023; Zhu *et al*., 2021).

2.2.3. Ironwood Seedling Preparation

Preparation for ironwood seedling nurseries began by wounding the ironwood seeds with a knife around the growing point, with a wound approximately 2–3 mm long. This was done to eliminate the dormancy of the ironwood seeds. The ironwood seeds were soaked in water at a temperature of approximately 50°C until the water cools. The ironwood seeds were inserted in the soil (polybags of 20×30 cm) with tilted position (the growing point parallel to soil surface).

2.2.4. Maintenance and Observation

Ironwood seedlings were maintained by watering them sufficiently in the morning and evening. During heavy rainfall, the ironwood seedlings were watered when the soil appeared dry. After the ironwood seedlings were three months old, they were divided into three groups: treatment 1 or the control group (AC0), treatment 2 (AC20), and treatment (AC200). Treatment 1 or the control group consisted of ironwood seedlings without liquid smoke irrigation. Treatment 2 consisted of ironwood seedlings treated with liquid smoke at a ratio of 1:20, while treatment 3 consisted of ironwood seedlings treated with liquid smoke at a ratio of 1:200. Each group consisted of five ironwood seedlings. The ironwood seedlings were watered with a mixture of 200 mL of liquid smoke and water every two weeks. Observations of the seedlings' growth were conducted every two weeks, including counting the number of leaves and measuring the plant height and stem diameter of the seedlings.

2.2.5. Growth Characteristics of Ironwood Seedlings

Observations on the agronomic characteristics of ironwood seedlings included plant height increase, stem diameter increase, and number of leaves. The leaves counted on ironwood seedlings were those that had fully opened. Ironwood seedling height was measured using a 1-meter plastic ruler. The diameter of the ironwood seedlings was measured using calipers at a distance of 1 cm from the base of the stem.

Observations on the agronomic characteristics of ironwood seedlings were first conducted after the plants were 3 months old (designated as P1). Subsequent observations were conducted every 2 weeks for 8 observations (14 weeks after the first observation).

2.3. Data Analysis

The agronomic data was analyzed using ANOVA (analysis of variance). If the liquid smoke application is significant, the analysis was continued with LSD (least significant difference) test at a significant level of 5%.

3. RESULTS AND DISCUSSION

3.1. Liquid Smoke Compounds

The GCMS analysis of liquid smoke from sago processing solid waste showed the presence of organic compounds, characterized by the formation of peaks on the Y-axis. The highest peak, peak 11, had a retention time of 4.123 minutes (Figure 2), while the organic compound with the largest area was peak 18, with a retention time of 10.011 minutes (Table 1). Peak 11 had a lower retention time than peak 18, as the retention time is the time required to reach the maximum peak. Therefore, although peak 18 was lower than peak 11, the retention time required to reach the maximum peak was longer. The chemical compound detected in peak 18 was phenol with an area of 20.54%, while the chemical compound detected in peak 11 was acetic acid with an area of 17.85%. Phenolic compounds are classified as phenols and acetic acid is classified as acid. Acetic acid in the liquid smoke of sago processing waste was also detected in 3 other peaks, namely peak 2 with a retention time of 2.343 minutes, peak 3 with a retention time of 2.463 minutes and peak 4 with a retention time of 2.558 minutes. This makes acetic acid the highest compound in the liquid smoke of sago processing waste compared to other compounds with a total area of 35.56%. Based on the results of the pH test of the liquid smoke of sago processing solid waste of 2.5, it shows that acetic acid contributes to the acidic nature of the liquid smoke of sago processing solid waste. The results of this study are also in line with the results of previous studies which stated that acetic acid is the dominant compound in liquid smoke made from agricultural waste, forest biomass and wood waste (Omulo *et al*., 2017; Aguirre *et al*., 2020; Mahdie *et al*., 2020), so that the pH of liquid smoke is in the range of pH 2–4 (Theapparat *et al*., 2018).

In Figure 2, the X-axis represents the observation time, while the Y-axis shows the peak formation or the presence of the detected compound. The retention time is the time required for the compound to reach its maximum peak. The area in percentage is not determined from the Y-axis, but from the area. The area indicates the amount of a compound present; a larger area indicates a higher amount of the detected compound (Zhu *et al*., 2023). For example, peak 18, with a retention time of 10.011 min, has a low Y-value but the largest area formed.

For compounds with retention times greater than one min, no information from the laboratory assistant is obtained. Speculatively, we think that compounds with longer retention times indicate higher concentrations of that compound (in this case, acetic acid) compared to other compounds. This is supported by several references that acetic acid is the dominant compound in liquid smoke (Grewal *et al*., 2018; Zhu *et al*., 2021; Oramahi *et al*., 2021).

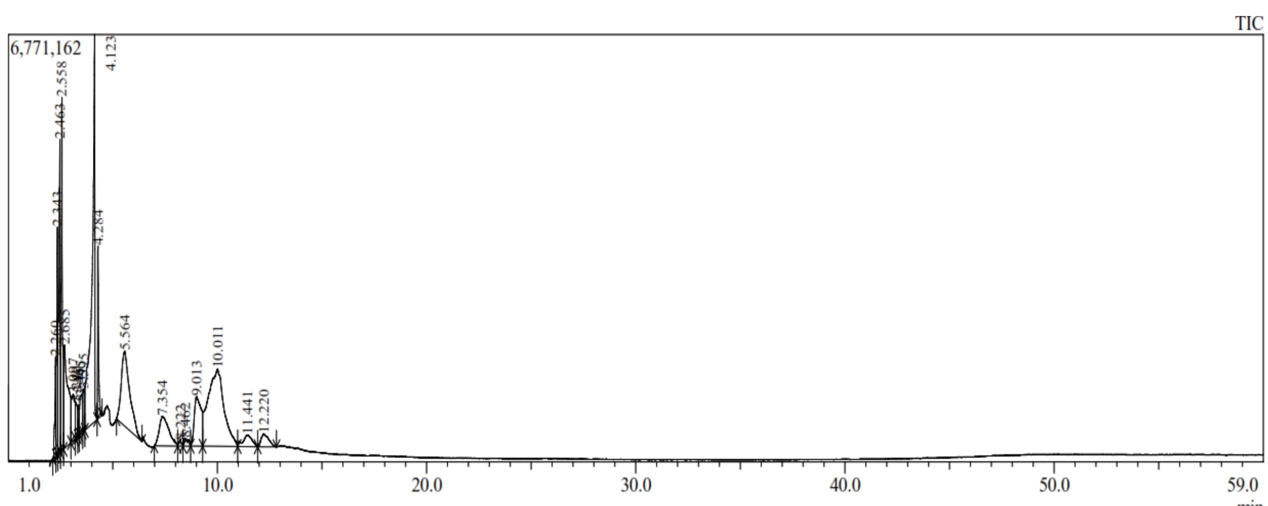

Figure 2. Chromatogram of liquid smoke produced from solid waste of sago processing

Table 1. Results of GCMS analysis of liquid smoke produced from solid waste of sago processing

Peak	Retention Time (min)	Compound Name	Group	Chemical Formula	Area (%)
1	2.260	Hydrazine, 1,2-dimetil-	-	$C_2H_8N_2$	1.58
2	2.343	Acetate	Acid	$C_2H_4O_2$	3.67
3	2.463	Acetate	Acid	$C_2H_4O_2$	6.76
4	2.558	Acetate	Acid	$C_2H_4O_2$	7.28
5	2.685	2-Butanon	Ketone	C_4H_8O	7.25
6	3.097	2-Butanon, 3-metil-	Ketone	$C_5H_{10}O$	2.63
7	3.240	Butanoate, 3-metil-	Acid	$C_5H_{10}O_2$	1.14
8	3.346	2-Pentanon	Ketone	$C_5H_{10}O$	0.64
9	3.445	Digitoxose	-	$C_6H_{12}O_4$	1.79
10	3.595	Metil glioksal	Phenol	$C_3H_4O_2$	1.18
11	4.123	Acetate	Acid	$C_2H_4O_2$	17.85
12	4.284	2-Propanon, 1-hdroksi-	Ketone	$C_3H_6O_2$	2.47
13	5.564	Furfural	Furan	$C_5H_4O_2$	10.62
14	7.354	2-siklopenten-1-one, 2-metil-	Ketone	C_6H_8O	4.68
15	8.222	2-siklopenten-1-one, 2,3-dimetil-	Ketone	$C_7H_{10}O$	0.25
16	8.462	Sikloktana	Ether	C_8H_{14}	0.58
17	9.013	2-Furankarboksaldehida, 5-metil-	Furan	$C_6H_6O_2$	5.68
18	10.011	Phenol	Phenol	C_6H_6O	20.54
19	11.441	2-siklopenten-1-one, 2,3-dimetil-	Ketone	$C_7H_{10}O$	1.75
20	12.220	Phenol, 2-metil-	Phenol	C_7H_8O	1.63

The chemical compounds that make up liquid smoke from solid waste from sago processing are 20 types (Table 1). This number is higher than the number of compounds in liquid smoke from date palm trunks produced at 350°C - 400°C (Ebrahimi *et al*., 2022). Date palms are a type of monocot, the same as sago palms, but the number and types of compounds that make up their liquid smoke differ. This is because the heating rate during the pyrolysis process is different (de Medeiros *et al*., 2019). Furthermore, these two liquid smokes have different raw materials, even though they are classified as monocot plants. The rapid heating rate causes the amount of liquid smoke produced to increase because the rapid heating rate causes the biomass to reach the pyrolysis temperature quickly, so that the biomass that has been converted to smoke will leave the reactor and undergo cooling before secondary reactions or secondary heating can result in a decrease in liquid smoke production. The presence of secondary reactions can produce other types of compounds or affect the amount of certain types of compounds (Basu, 2013). Differences in the number and types of compounds that make up liquid smoke can be used as indicators to identify the origin of the raw materials. Hydrazine compounds found in liquid smoke from sago processing waste can be used as a marker for sago biomass because they were also found in GCMS analysis of sago waste extracts (Siruru *et al*., 2019) and were not found in other materials, such as liquid smoke of *Shorea laevis* (Oramahi *et al*., 2020), *Eucalyptus urograndis* and *Mimosa tenuiflora* (de Medeiros *et al*., 2019), as well as *Phoenix dactylifera* (Ebrahimi *et al*., 2022).

Acetic acid, phenols, and furans are the dominant compounds in liquid smoke from sago processing waste (Table 1). According to Grewal *et al*. (2018), organic acids, such as acetic acid, in liquid smoke can dissolve phosphoric acid, making it more easily absorbed by roots and increasing phosphoric acid levels. Phenolic compounds contribute to inhibiting fungal growth (Oramahi *et al*., 2020) and their derivatives serve to prevent pest attacks because they are toxic to insects which can cause continuous fluid loss in insects (Malvini & Nurjasmin, 2019). In addition, acetic acid and phenol can be used as natural fungicides and pesticides (Hagner, 2013). According to Purwantisari *et al*. (2023) the phenol content in liquid smoke has antifungal activity where phenol can interfere with cell metabolism and fungal enzymes. Phenolic compounds inhibit the working system of fungal enzymes, prevent the growth of hyphal tips, neutralize enzymes involved in fungal invasion, damage fungal cell membranes, and interfere with nucleic acid production in fungi (Alfiah *et al*., 2015). The compounds found in liquid smoke from sago processing solid waste do not contain hazardous compounds such as polycyclic aromatic hydrocarbons (PAHs) so they are safe for use. Successful plant growth is not solely dependent on nutrient availability but is also influenced by the soil, a complex ecosystem that harbors bacteria, fungi, protists, and animals. Efforts to eliminate or defeat pathogenic microbial strains can enhance plant growth (Jacoby *et al*., 2017).

Plant growth is influenced by various factors, but under normal conditions (without pest or disease attack), the most dominant factors are nutrient availability and the plant's ability to absorb them. In this case, liquid smoke does not contribute to nutrient supply but facilitate nutrient availability, making them more available to plants.

3.2. Height Increase of Ironwood Seedlings

The effect of using or applying liquid smoke from sago processing waste on ironwood seedlings was observed through observations of the increase in height (Table 2), diameter (Table 3), and number of leaves (Table 4). Height, diameter, and number of leaves were first measured by taking an initial measurement (P1) as a baseline to determine the increase in height, diameter, and number of leaves of ironwood seedlings. The results of the second measurement (P2) were subtracted from the first measurement (P1) to determine the increase in height, diameter, and number of leaves of ironwood seedlings. Based on the ANOVA, liquid smoke from sago processing waste had no effect on the increase in height of ironwood seedlings from the first to the eighth observations. This is likely because liquid smoke from sago processing waste does not contain compounds that can promote plant growth, such as methyl acetate and methyl formate, which are classified as ester compounds (Grewal *et al*., 2018). Successful cell division is inseparable from the performance of photosynthesis, which produces sugar, a key component in plant metabolism.

Liquid smoke is an organic compound and does not contain nutrients (inorganic elements). The role of liquid smoke on plant growth is indirect, such as conditioning the growing medium, including its biological, chemical, and physical properties, making the soil more suitable for plant growth. Plant height growth is influenced by cell division at the growing point. The apical meristem at the growing point plays a crucial role in vertical plant growth (Dilla *et al*., 2023). The more cell division occurs in the apical meristem, the faster the plant will grow. Adding liquid smoke from sago solid waste at ratios of 1:20 and 1:200 to ironwood seedlings did not provide additional nutrients that could support cell division at the growing point. According to Karjadi *et al*. (2022), the availability of macro- and micronutrients is one factor that encourages cell division at the growing point.

Table 2. Height increase of ironwood seedlings (cm)

Treatment	**Observation**						
	2	**3**	**4**	**5**	**6**	**7**	**8**
AC 0 (Control, no liquid smoke)	1.64	2.44	3.28	6.24	9.14	9.74	10.64
AC 1 (with liquid smoke, ratio 1:20)	3.20	3.40	4.00	4.74	6.14	6.78	6.86
AC 2 (with liquid smoke, ratio 1:200)	3.42	4.20	6.20	6.50	8.80	9.50	10.30

Table 3. Increase in diameter (cm) of ironwood seedlings

Treatment	**Observation**						
	2	**3**	**4**	**5**	**6**	**7**	**8**
AC 0 (Control, no liquid smoke)	0.39	0.74	0.99	1.34	1.44	1.51	1.76
AC 1 (with liquid smoke, ratio 1:20)	0.34	0.54	0.81	1.02	1.26	1.47	1.58
AC 2 (with liquid smoke, ratio 1:200)	0.28	0.48	0.71	0.90	1.10	1.20	1.46

3.3. Diameter Increase of Ironwood Seedlings

The increase of stem diameter (Table 3) implies horizontal growth of dicotyledonous plants which is influenced by the activity of the lateral meristem. The lateral meristem consists of vascular cambium, which can divide outward to form the bark and inward to form the stem, resulting in plant growth. Newly formed cells, both bark and wood, subsequently undergo cell wall thickening. This cell wall thickening requires sugars produced through photosynthesis to form carbohydrates and lignin. The rate of photosynthesis production is also influenced by the availability of nutrients in the growing medium. Based on the results of the ANOVA, the increase in diameter of ironwood seedlings was not significantly affected by the application of liquid smoke from sago processing waste in each observation. This is because the growing medium, ultisol soil, generally contains limited or poor nutrients (Siruru, 2021), and the dosage of liquid smoke administered was not appropriate for increasing soil microbial activity. According to Koç *et al*. (2019), liquid smoke can positively impact biological activity in the soil at a dose of 3.0% mL.

3.4. Increase in Leaf Number of Ironwood Seedlings

Based on the ANOVA results, liquid smoke application significantly affected the increase in leaf number of ironwood seedlings only at the second observation (Table 4). In contrast, no significant effect was observed from the third to the eighth observations. The highest value (5.00) was found in the liquid smoke treatment with a 1:20 ratio (AC 1), while the lowest value was found in the treatment without liquid smoke (AC 0). The results of observations on the number of ironwood seedlings' leaves in all treatments indicated that ironwood seedlings did not produce leaves during the specified time period. The treatment without liquid smoke (AC 0) from observations 3 to 5 showed no leaf increase (2.60). The liquid smoke treatment with a ratio of 1:20 (AC 1) in observations 7 and 8 showed no increase in leaves (10.20), and the liquid smoke treatment with a ratio of 1:200 (AC 2) in observations 4 and 5 showed no increase in the number of leaves (5.00). In addition, the liquid smoke treatment with a ratio of 1:200 (AC 2) in observation 6 showed a decrease in the number of ironwood seedling leaves, namely 7.20 to 6.60 in observation 7. This is because in addition to the plant continuing to form new leaves, the plant can also shed leaves. Naturally, plants shed leaves due to the aging process. Leaves will fall based on the age of the leaves, which generally starts from the lowest leaves because they are the first to form. However, it is not uncommon for plants to also shed leaves that have not yet experienced senescence. Liquid smoke has a phytotoxic effect and has the potential to be used as a natural herbicide for weed control. Acetic acid is likely the main active ingredient causing the phytotoxic effect (Chu *et al*., 2022). According to Aguirre *et al*. (2020), liquid smoke at concentrations ranging from 25% to 100% caused only temporary injury to silver wattle (*Acacia dealbata* Link), a woody perennial, while white mustard, an annual broadleaf weed, completely dried out. These results differ from those of Luo *et al*. (2019), which showed that the use of liquid smoke enhance tomato plant growth.

Table 4. The increase number of leaf of ironwood seedlings

Treatment	**Observation**						
	2	**3**	**4**	**5**	**6**	**7**	**8**
AC 0 (Control, no liquid smoke)	0.80^{a}	2.60	2.60	6.00	7.20	8.80	8.60
AC 1 (with liquid smoke, ratio 1:20)	5.00^{b}	5.00	5.80	6.60	9.40	10.20	10.20
AC 2 (with liquid smoke, ratio 1:200)	2.20^{ab}	4.20	5.00	5.00	7.20	6.60	7.60

4. CONCLUSION

Liquid smoke produced from sago solid waste contains various groups of compounds, including acids, ketones, phenolics, furans, ethers, and other minor components, with acetic acid being the most abundant compound. Hydrazine can be used as a marker compound for liquid smoke derived from sago solid waste, as it was also detected in the GC–MS analysis of sago solid waste extractives. In addition, phenolic compounds were among the dominant components after acetic acid, indicating that liquid smoke from sago solid waste has potential for application as a natural pesticide and as an antifungal agent in wood preservation. However, the application of liquid smoke to ironwood seedlings did not significantly affect agronomic parameters, including plant height, leaf number, and stem diameter.

AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
HS	✓	✓	✓						✓	✓				✓
WNI														✓
IB	✓	✓								✓				✓

C: Conceptualization
M: Methodology
So: Software
Va: Validation
Fo: Formal Analysis
I: Investigation
D: Data Curation
R: Resources
O: Writing - Original Draft
E: Writing - Review & Editing
Vi: Visualization
Su: Supervision
Fu: Funding Acquisition
P: Project Administration

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