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Research Paper

Optimization and Characterization of Liquid Smoke Produced by *Terminalia catappa* Wood Pyrolysis and its In Vitro Antifungal Activity

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Abstract

This research utilized response surface methodology (RSM) to explore how the yield of liquid smoke obtained from ketapang wood (*Terminalia catappa*) is influenced by the size of wood particles and the temperature of pyrolysis. Gas chromatography-mass spectrometry (GC-MS) was used to characterize the liquid smoke. To assess liquid smoke's antifungal effects, a petri dish bioassay was conducted using 1.0-4.0% (v/v) concentrations against *Schizophyllum commune*. RSM was applied to optimize vinegar from *T. catappa* by varying the wood particle size and the pyrolysis temperature. The optimal yield, 24.67%, was obtained with a 3.22 mm particle size and a 425°C pyrolysis temperature. The liquid smoke produced at 400-450°C completely inhibited of *S. commune* growth at 2.0-4.0%. The primary components of the liquid smoke at 400°C were 2-methoxy- phenol (24.85%), creosol (8.39%), 4-ethyl-2-methoxy- phenol (7.21%), 2-5-methyl-furancarboxaldehyde (4.55%), and 4-ethyl-2-methoxy-phenol (3.74%). The primary components at 425°C were 2-methoxy-phenol (25.60%), creosol (15.15%), 5-methyl-2-furancarboxaldehyde (12.75%), and 2,6-dimethoxy-phenol (9.31%). At 450°C, the main components were 2-methoxy-phenol (25.26%), 4-ethyl-2-methoxy-phenol (8.46%), creosol (8.40%), 5-methyl-2-furancarboxaldehyde (4.02%), and 4-ethyl-2-methoxy-phenol (3.98%).

Keywords

Liquid Smoke, *Terminalia catappa*, Response Surface Methodology, Pyrolysis Temperature, Wood Particle Size, Antifungal Activity

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1. INTRODUCTION

The response surface methodology (RSM) involves mathematical and statistical techniques to construct models and assess the impacts of various independent variables, along with their interactions. The primary goal is to enhance the response, as highlighted by Barbanera et al. (2018) and Yuan et al. (2018). Notably, RSM has demonstrated success in optimizing liquid smoke production from barley straw Zhu et al. (2018) and *Acacia nilotica* Singh et al. (2020) through pyrolysis. Oramahi et al. (2020) investigated the optimization of operational parameters for liquid smoke production from *Shorea laevis* Ridl. They determined that the optimal pyrolysis conditions were achieved at a temperature of 400°C, a particle size of 3.85 mm, and a pyrolysis time of 93 minutes, resulting in a yield of 30.31%. In another study, Zhu et al. (2018) utilized RSM to examine the impact of reaction temperature (260–340°C), reaction time (5–25 minutes), catalyst dosage (2-18%), and biomass-to-water ratio (9-12%) on the fast pyrolysis of barley straw, achieving an optimal liquid smoke yield of 38.72%.

Recently, Oramahi et al. (2022a) showed that RSM can also predict the liquid smoke yield obtained from *Shorea pachyphylla*. The results showed that the optimum liquid smoke yield was 31.31% at a pyrolysis time and temperature of 124 minutes and 440°C. The pyrolysis temperature factor significantly influenced the liquid smoke yield, whereas the time factor had no effect on it. Recently, Hasan et al. (2023) used analysis of variance (ANOVA) to confirm that the optimum liquid smoke yield from macadamia nutshell is influenced by temperature, residence time, and feedstock particle size. Fan et al. (2014) used analysis of variance (ANOVA) to confirm that the optimum yield of liquid smoke is predisposed by pyrolysis temperature, heating rate, reactor pressure and holding time were 19.4 °C/min, 495.5°C, 5.0 kPa, and 50 min, respectively.

A number of researchers have measured liquid smoke yields to determine the optimal operating conditions. Several factors strongly influence the optimal liquid smoke yield, including the size of the raw material and the pyrolysis time and temperature (Crespo et al., 2017). Liquid smoke gained from various biomass sources has been found to be a safe natural antifungal (Oramahi et al., 2010; Subekti and Yoshimura, 2020; Ramos et al., 2020) and antitermitic agent (Oramahi et al., 2014; Oramahi et al., 2022b).

The effectiveness of liquid smoke in preventing fungal growth is predisposed by its chemical composition, which, in turn, is impacted by various factors such as the levels of cellulose, hemicellulose, and lignin, along with the pyrolysis temperature during production. Variations in the chemical constituents of liquid smoke, including the phenol and acid groups, are thought to affect its ability to inhibit fungal growth. The temperature of pyrolysis during liquid smoke production is a crucial factor, causing alterations in the smoke's chemical content (Oramahi et al., 2022a). The liquid smoke gained from durian wood at temperatures ranging from 350–450°C displayed antitermitic agent (Suprianto et al., 2023).

Hou et al. (2018) observed that liquid smoke produced at temperatures ranging from 450 to 480°C exhibited antifungal activity against Penicillium, Aspergillus, and Rhizopus. Chen et al. (2020) utilized *Cinnamomum parthenoxylon* liquid smoke to safeguard stored grapes against *Botrytis cinerea*. Ramos et al. (2020) described that liquid smoke derived from cattle manure at 400°C displayed antifungal activity against *Lasiodiplodia theobromae* and *Fusarium solani*. The assessment of liquid smoke impact on the mycelium growth of Curvularia and Pestalotiopsis species in vitro showed promising results when measuring colony diameter. The highest inhibition percentages were 23.35% for Curvularia and 28.56% for Pestalotiopsis species. The concentration with the most significant inhibitory effect (3.35% v/v) recorded a 28.56% inhibition for Pestalotiopsis species (Obeng et al., 2023).

However, it's noteworthy that liquid smoke from ketapang wood (*Terminalia catappa*) has not undergone previous assessments for optimal yield, characterization, or evaluation of its antifungal activity. Wood-decaying fungi, such as *Schizophyllum commune* are capable of decomposing cellulose and lignin, which leads to the deterioration of wood and a rapid decline in the strength of its flexible fibers (Anggraini et al., 2021).

The objective of this study was to employ RSM to optimize the yield of liquid smoke from *T. catappa*. The chemical component of the liquid smoke was analyzed using gas chromatography–mass spectrometry (GC–MS). We also investigated the antifungal effectiveness of *T. catappa* liquid smoke against *Schizophyllum commune*.

2. EXPERIMENTAL SECTION

2.1 Materials

Ketapang wood (*Terminalia catappa*) was acquired from the Wood Workshop Laboratory at Fakultas Kehutanan, Universitas Tanjungpura, Pontianak. Subsequently, the wood was segmented into pieces measuring 0.841 mm, 1.680 mm, and 4.764 mm.

2.2 Methods

Wood particles were pyrolyzed using the methods outlined in a previous study (Oramahi et al., 2019; Oramahi et al., 2021). The process involved introducing wood particles into a pyrolysis reactor. Pyrolysis was conducted at 350, 400, and 450°C, each for a duration of 180 minutes.

2.2.1 Experimental Design and Optimization of Liquid Smoke

RSM, refers to a collection of mathematical and statistical methods utilized for modeling and scrutinizing responses in experimental settings.These responses are influenced by various independent variables. The optimization of these responses is the goal of RSM (Montgomery, 1991).

The present study used RSM with a central composite face-centered experimental design that was chosen on the basis of recent literature (Nam and Capareda, 2015). Two influential factors, namely the wood particle size and pyrolysis temperature, were optimized in this study. The particle sizes examined were 0.841, 1.680, and 4.764 mm. Table 1 lists the levels of variables used for the central composite face-centered experimental design matrix.

Table 1. Levels of Variables Employed in the Central Composite Face-Centered Experimental Design Matrix

Independent Variable	Symbol	Coded Variable Level Low -1	 Center 0	 High 1
Wood particle size (mm)	X1	0.841	1.680	4.764
Pyrolysis temperature (°C)	X2	350	400	450

The equation representing the second-order polynomial, including all interaction terms, can be expressed in Equation (1) as follows:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i} \sum_{j} \beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

In this context, $\beta_0$signifies the constant regression coefficient, while and β_i, β_{ii} and β_{ij} represent the regression coefficients associated with linear, quadratic, and interaction effects. The variables terms x_i, x_j stand for the independent factors, and and ε indicates the error term.

2.2.2 Chemical Components of Liquid Smoke Obtained from *Terminalia catappa*

The chemical composition of liquid smoke derived from *T. catappa* was assessed through GC-MS using a QP-210S instrument (Shimadzu, Japan). Analysis of GC-MS employed capillary columns (30 m × 0.25 mm), and the temperature of injection (250°C) and the column temperature (60-200°C). Helium was employed as the carrier gas with a 40.0 mL/min flow rate, while the interface temperature was consistently held at 200°C. The method entailed injecting a liquid sample volume of 1 mL, and the temperature was controlled within the range of -°C, increasing gradually at a rate of 5°C/minute. Compounds in the liquid smoke were acknowledged by comparison them with data from the standard library (Mun and Ku, 2010), and their concentrations were determined based on integrated peak areas.

2.2.3 Determination of Total Phenol

The quantification of total phenol content in *T. catappa* liquid smoke followed the outlined procedures by Senter et al. (1989). Initially, a 1 mL sample of liquid smoke was diluted with Aquabides. Subsequently, 1 mL of the resulting diluted sample was combined with a 5 mL solution containing 2% sodium carbonate. After a 10-minute incubation, 0.5 mL of Folin Ciocalteau suspension was introduced to the solution. Additionally, the absorbance of the resulting solution at 750 nm was meticulously measured using a UV-Vis spectrophotometer. The concentration of total phenols in each liquid smoke sample was resolute by comparing it with the concentration in a pure phenol suspension.

2.2.4 Determination of Acidity

The acidity of *T. catappa* liquid smoke was resolute following the AOAC (1990) procedure. A 1 mL volume of liquid smoke was diluted to 100 mL with Aquabides. Subsequently, three drops of phenolphthalein (PP) indicator were added, and the solution was felt titration using 0.1 N NaOH.

2.2.5 Fungal Cultures and Inhibition Test

The efficacy of liquid smoke, obtained through pyrolysis at temperatures between 400-450°C was evaluated for its antifungal properties against *Schizophyllum commune*. The assessment of the inhibition rate against the fungi followed the procedure by Adfa et al. (2020). In brief, *S. commune* cultures were cultivated for 7 days on PDA at 27°C and used as inoculants. PDA media with varying concentrations of liquid smoke (0% as control, 1.0%, 2.0%,3.0%, and 4.0% v/v) were sterilized and poured into petri dishes (90 × 20mm, Asahi Glass Manufacturing, Japan) by autoclaving at 121°C and 103.4 kPa (15 psi) for 15 minutes. The PDA plates were inoculated at their centers with a singular plug. Subsequently, both treated and untreated dishes underwent a 7-day incubation in a controlled environment at 27°C. Daily measurements of colony diameters were taken, and the mycelia inhibition rate was determined using Equation (2).

$$I = \frac{(Du - Dt)}{Du} \times 100 \tag{2}$$

In this equation, I represents the inhibition percentage, and Du and Dt denote the mycelia diameters of untreated and treated dishes in milimeters, respectively.

2.2.6 Statistical Analysis

The RSM results were statically evaluated using Statistic and SAS. The antifungal test results were presented as means and standard deviations and they underwent one-way ANOVA. Tukey's highly significant difference (HSD) test was utilized to differentiate means, with a significance level established at p = 0.05. The experiments were conducted four times. All data analyses were performed using SAS.

3. RESULTS AND DISCUSSION

3.1 Maximizing the Yield of Liquid Smoke from *Terminalia catappa*

The influences of two variables, namely wood particle size (X1) and pyrolysis temperature (X2), on liquid smoke yield from *Terminalia catappa* (observed and predicted) were investigated using RSM as shown in Table 2.

Table 2. Response Surface Methodology Configuration Detailing the Observed Response and Predicted Values for the Liquid Smoke Yield Obtained from *Terminalia catappa*

Run	Level and Variable Coded		Liquid Smoke Yield (Y,%)	
	X1	X2	Observed	Predicted
1	-1	-1	10.56	14.81
2	1	-1	16.67	21.59
3	-1	1	22.78	14.81
4	1	1	22.78	21.59
5	-1	0	15.00	18.72
6	1	0	20.56	16.84
7	0	-1	8.89	12.61
8	0	1	25.00	21.28
9	0	0	21.11	21.81
10	0	0	19.44	21.81
11	0	0	20.00	21.81
12	0	0	26.67	21.81

The optimal operating conditions for the process were 24.67% liquid smoke from *T. catappa* with a 3.222 mm particle size and a pyrolysis temperature of 425°C. The factor contributing to the maximization of liquid smoke yield was pyrolysis temperature; wood particle size had a negligible effect in this study. Similar results were described by Mandal et al. (2018), Onay and Koca (2020), and Oramahi et al. (2022a). The coefficient of variation for predicting liquid smoke yield was determined to be 24.21%. These results suggested that the developed model is effective in forecasting the liquid smoke yield from *T. catappa* (Table 3). The significance of the second-order polynomial model is evident, supported by a low F-test value ($p<0.05$) in predicting liquid smoke yield. Oramahi et al. (2022b) emphasized the significance of temperature as a predictive factor for yield of liquid smoke obtained from *Shorea pachyphylla*. The regression coefficients can be found in Table 3.

The determination coefficient (R^2) for liquid smoke yield was 0.61, indicating that the model can account for 61% of the variability, leaving 39% residual variability for the *T. catappa* liquid smoke yield. Oramahi et al. (2022a) and Li et al. (2017) reported comparable outcomes with increased variability in the model's results. Oramahi et al. (2022b) suggested that a higher R^2 value implies the model's efficiency in predicting liquid smoke from *Shorea pachyphylla*.

Figures 1 and 2 display a 2D contour plot in two dimensions and 3D response surface curves. These figures, illustrate

Table 3. Regression Coefficients for the Anticipated Quadratic Polynomial Model

Source of Variation	Polynomial Coefficient	Error	t-value	Pr>t
Intercept	21.65	2.15	10.06	<0.0001
X1	4.84	2.49	1.94	0.1003
X2	6.31	2.44	2.58	0.0415
X1*X1	-3.56	3.09	-1.15	0.2929
X2*X1	-2.38	3.27	-0.73	0.4950
X2*X2	-4.39	3.09	-1.42	0.2046

Coefficient of variation = 24.21%, R^2 = 0.61

the impact of wood particle size and pyrolysis temperature on the liquid smoke yield. The optimal conditions for the independent variables are a particle size (3.22 mm) and a pyrolysis temperature (425 °C).

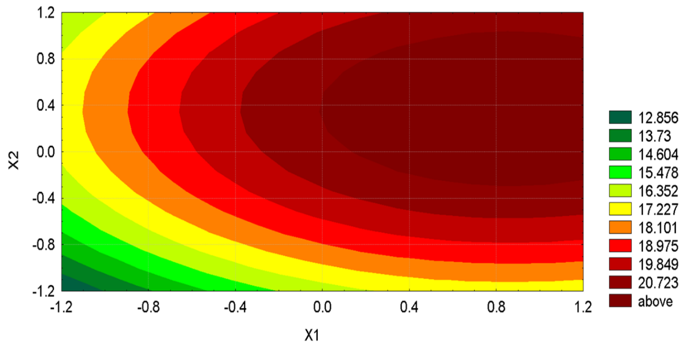

Figure 1. Contour Plot Illustrating the Impact of Wood Particle Size and Pyrolysis Temperature on the Liquid Smoke Yield

The fitted model for liquid smoke yield (%) to predict the relationship between the independent variables and the response can be expressed by Y = 21.65 + 4.84 X1 + 6.31 X2 – 3.56 $X1^2$ – 2.38 X1.X2 – 4.39 $X2^2$.

In addition, the canonical equation reflecting the shape of the graph by looking at the eigenvalues is as follows (Equation (3)):

$$Y = 24.67 - 2.71W_1^2 - 5.24W_2^2 \qquad (3)$$

The values obtained are all negative, indicating that the graph represents a maximum (Figures 1 and 2).

Similar experiments to those outlined in this description were conducted by Hasan et al. (2023) with macadamia nutshell as the feedstock. In their research, they effectively identified the optimal experimental conditions by ensuring that all independent variables fell within the designated range, and the response (liquid smoke yield) was optimized.

3.2 Chemical Composition of Liquid Smoke from *Terminalia catappa*

Tables 4-6 present the results of the GC–MS chemical analysis conducted on liquid smoke obtained from *T. catappa*. In Table 4, the dominant components of liquid smoke from ketapang wood, identified through GC–MS analysis at 400°C, comprised 2-methoxy-phenol (24.85%), creosol (8.39%), and 2-5-methyl-furancarboxaldehyde (4.55%). In Table 5, the primary constituents of liquid smoke from ketapang wood, as revealed by GC–MS analysis at 425°C, included 2-methoxy-phenol (25.60%), creosol (15.15%), 5-methyl-2-furancarboxaldehyde (12.75%), and 2,6-dimethoxy-phenol (9.31%). At 450°C (Table 6), the principal compounds of liquid smoke from ketapang wood were 2-methoxy-phenol (25.26%), 4-ethyl-2-methoxy-phenol (8.46%), creosol (8.40%), 5-methyl-2-furancarboxaldehyde (4.02%), and 4-ethyl-2-methoxy-phenol (3.98%).

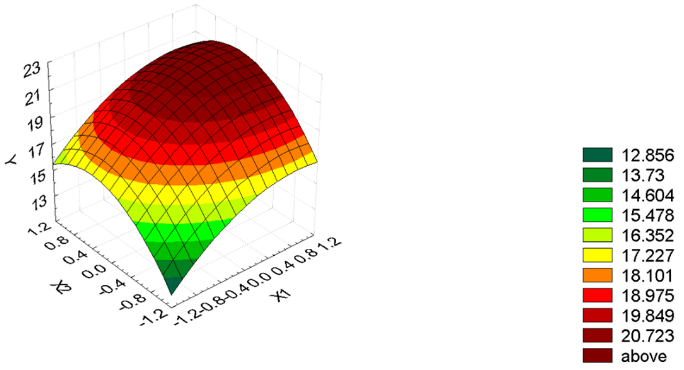

Figure 2. Three-dimensional Response Surface Curves Illustrating the Impact of Wood Particle Size and Pyrolysis Temperature on the Liquid Smoke Yield

Table 4. GC-MS Analysis of Liquid Smoke from *Terminalia catappa* at 400°C

RT (min)	Liquid Smoke Composition	Area (%)
3.96	2-Cyclopenten-1-one	3.55
4.05	Ethanone	4.46
4.55	2-Cyclopenten-1-one, 3,4-dimethyl-	1.10
5.13	5-Methyl-2-furancarboxaldehyde	4.55
5.98	2-Furanmethanol	1.02
6.10	trans-2-Methyl-4-hexen-3-ol	1.66
6.70	1,2-Cyclopentanedione, 3-methyl-	1.89
7.93	2-Methyl-oct-2-enedial	1.09
8.37	Phenol, 2-methoxy-	24.85
11.20	Creosol	8.39
13.57	4-Ethyl-2-methoxy-phenol	3.74
15.56	2,6-Dimethoxy-phenol	7.21

Similarly, Hou et al. (2018) analyzed liquid smoke from Eucommia ulmoides Olivers branches and identified six primary compounds: phenols, ketones, aldehydes, alcohol, organic acids, and benzenes. Ankona et al. (2023) reported that the principal compounds of liquid smoke from Citrus

Table 5. GC-MS Analysis of Liquid Smoke from *Terminalia catappa* at 425°C

RT (min)	Liquid Smoke Composition	Area (%)
3.98	2-Cyclopenten-1-one, 2-methyl-	2.28
4.08	Ethanone, 1-(2-furanyl)-	3.97
5.15	2-Furancarboxaldehyde, 5-methyl-	12.75
6.71	3-Methylcyclopentane-1,2-dione	1.50
8.37	2-Methoxy-phenol	25.60
11.22	Creosol	15.15
13.63	4-Ethyl-2-methoxy-phenol	7.77
15.61	2,6-Dimethoxy-phenol	9.31
18.05	3,5-Dimethoxy-4-hydroxytoluene	4.96
19.99	5-tert-Butylpyrogallol	2.90

Table 6. GC-MS Analysis of Liquid Smoke from *Terminalia catappa* at 450°C

RT (min)	Liquid Smoke Composition	Area (%)
3.93	2-Cyclopenten-1-one, 2-methyl-	2.58
4.05	Ethanone, 1-(2-furanyl)-	2.76
5.12	2-Furancarboxaldehyde, 5-methyl-	4.02
5.89	2-Cyclopenten-1-one, 2,3-dimethyl-	1.64
6.09	1,6-Heptadien-4-ol	1.89
6.69	1,2-Cyclopentanedione, 3-methyl-	1.84
6.93	2-Cyclopenten-1-one, 2,3-dimethyl-	1.51
8.37	2-Methoxy-phenol	25.26
11.19	Creosol	8.40
13.56	4-Ethyl-2-methoxy-phenol	3.98
15.56	2,6-Dimethoxy-phenol	8.46
18.02	3,5-Dimethoxy-4-hydroxytoluene	1.54

limon produced at temperature ranging 350 to 500°C contained 2.41% butanoic acid, 12.07% 3-Hydroxy-3-methyl-2-butanone (methylacetoin), 2.93% 1-(2,3,4-trihydroxyphenyl) ethenone, 2.86% p-cresol, 12.25% syringol, 7.78% 1,2-benzenediol, 1.50% 3-methyl-1,2-benzenediol (3-methylpyrocatechol), 2.64% 4 ethyl 1,3-benzenediol (resorcinol), 4.36% benzene-1,4-diol (Hydroquinone). Meanwhile, the main component at temperature ranging 250–350°C including 0.14% butanoic acid, 5.13% 3-Hydroxy-3-methyl-2-butanone (methylacetoin) 3.78% 1-(2,3,4-trihydroxyphenyl) ethenone, 2.13% p-cresol, 10.44% syringol, 2.15% 1,2-benzenediol, and 1,80% 2-methoxy phenol (guaiacol), 1.05% 2,3-dimethylphenol (o-xylenol), 2.64% 4 ethyl 1,3-benzenediol (resorcinol), 2.15% 1,2-benzenediol (pyrocatechol), 2.96% 1,2,3-trimethoxybenzene (methylsyringol).

Faisal et al. (2023) employed RSM with two operational factors, namely pyrolysis temperature and pyrolysis duration, for the generation of liquid smoke obtained from *Durio zibethinus* Murr. Through their analysis, the optimal conditions for producing liquid smoke were identified as 347°C for pyrolysis temperature and 99.4 minutes for pyrolysis time. The primary chemical constituents comprised 74.98% acetic acid (CAS) ethylic acid and 6.19% phenol (CAS) izal. Oramahi et al. (2022a) reported that liquid smoke from *Shorea pachyphylla* mainly contained formic acid, 2-propanone, acetic acid,4-hexadecanoic acid, and guaiacol. Recently, Oramahi et al. (2023) investigated that the predominant compounds in liquid smoke gained from *Cinnamomum* sp. were 1,2-ethanadiol, acetic acid, phenol and methyl ester.

However, there are differences in the main compounds of liquid smoke from algal biomass, as reported by Jeeru et al. (2023). They found that liquid smoke contained p-xilene (1.08%), 2-methoxy-3H-azepine (1.2%), phenol (2,38%), phenil acetonitile (1.38%), 2-metyl-2-phenilpropanenitrile (1.35%), heneicosane (2.22%), syringol (1%), 4-methylpentanamide (9.8 %), n-hexadecanoic acid (4.77%), n-heptadecane (7.88%), undecenoic acid (3.2%), benzyl nitrile (2.86%) and 2-metyl naphthalene (5.21%), palmitic acid (2.1%), phytol (1.23%), and 3,4-dimethyl bensenamide (1.85%). Ngo et al. (2013) conducted pyrolysis at temperatures of 400 and 500°C and subsequently analyzed the resulting products to determine their reaction characteristics. The palm kernel cake liquid smoke at 400°C including 11.6% acetic acid, 7.88% 1-hydroxy-2-propanone, 1.68% furfural, 10.3% 2-furanmethanol, 1.34% 2-furancarboxylic, 5-methyl-, 2.84% phenol, 2.51% 1, 2-benzenediol, 3.06% 2, 3-o-acetonemannosan, 19.23% b-D-allose, 3.77% dodecanoic acid, and 9.34% 1, 2-benzenedicarboxylic acid, bis (2-ethylhexyl) ester. Meanwhile, at 500°C, the main components were 5.0% acetic acid, 3.1% 1-hydroxy-2-propanone, 5.0% 2-furanmethanol, 2.3% phenol, 2.7% 1, 2-benzenediol, 23.2% -D-allose, 11.2% dodecanoic acid, and 14.9% benzenedicarboxylic acid, bis (2-ethylhexyl) ester. Ates and Erginel (2016) identified liquid smoke from poplar sawdust at pyrolysis (500°C) and pressure (1 bar) were 3.38% acetic acid, methyl ester, 18.07% phenol, 1.16% 2,4-imidazolidinedione, 3-methyl- (1.16%), 1.57% 1,2-benzenediol, 3-methoxy-, 2.18% benzeneethanol, 2-methoxy-, 11.4% phenol, 2,6-dimethoxy-, 4.21% phenol, 2,6-dimethoxy-4-(2-propenyl)-, 1.06% hexadecanoic acid, and 3.06% 3,5-dimethoxy-4-hydroxycinnamalde.

3.3 Performance of Growth Inhibition Against *Schizophyllum commune*

Table 7 presents the percentages by which liquid smoke inhibits *Schizophyllum commune* growth at different pyrolysis temperatures and concentrations ranging from 1.0-4.0 (v/v). The *T. catappa* liquid smoke in the present study completely the growth inhibitory of *S. commune* fungus at 2.0-4.0 (v/v). Afrah et al. (2023) analyzed liquid smoke from rubber wood containing phenolic compounds and their various derivatives. The

Table 7. Evaluation of the Growth Inhibitory Effects of Liquid Smoke Obtained from *Terminalia catappa* at Different Pyrolysis Temperatures on *Schizophyllum commune* Cultured on PDA Media

Treatment		
Pyrolysis Temperature (°C)	Liquid Smoke Concentration (%)	Inhibition (%)
400	0	0 ± 0 a
	1.0	19.48 ± 4.56 b
	2.0	100 ± 0 d
	3.0	100 ± 0 d
	4.0	100 ± 0 d
425	0	0 ± 0 a
	1.0	29.50 ± 6.76 c
	2.0	100 ± 0 d
	3.0	100 ± 0 d
	4.0	100 ± 0 d
450	0	0 ± 0 a
	1.0	32.77 ± 5.70 c
	2.0	100 ± 0 d
	3.0	100 ± 0 d
	4.0	100 ± 0 d

[a] Means (*n* = 4). Values accompanied by distinct letters (a–c) indicate significant differences at a P-value less than 0.05 as determined by Tukey's test

chemical constituents of liquid smoke using GC-MS, revealing that the primary components were phenolic compounds and their different derivatives. The phenol yield was measured at 4.21%. The phenolic derivatives identified included phenol, 2-methoxy (6.55%), phenol, 4-methoxy-3-(methoxymethyl) (4.32%), and phenol, 4-ethyl-2-methoxy (3.81%). Additionally, the acidic component was butanoic acid (3.38%). Table 8 illustrates the characteristics of wood vinegars derived from *T. catappa* at various temperatures. These liquid smoke exhibited varying acid content, ranging from 4.48% to 5.08%, and phenol content fluctuated between 1.48% and 1.67%. Phenol exhibits effectiveness against a broad spectrum of microorganisms, including certain fungi (Ankona et al., 2023).

Akkuş et al. (2022) reported that liquid smoke showed antifungal activities against *Serpula lacrymans* and *Trametes versicolor*. The liquid smoke also showed antimold activities against *Apergillus niger* Tiegh, *Penicillium brevicompactum*, and *Trichoderma harzianum* Rifai. Ramos et al. (2020) suggested that the fungicidal activity of liquid smoke at 400°C from cattle manure could be attributed to phenolic compounds. Similarly, Permana et al. (2021) stated that phenolics and acids in liquid smoke could donate to antifungal activity agent. They attained liquid smoke from *Cinnamomum* sp. and found that it inhibited the growth of *S. commune*. Meanwhile, Theapparat et al. (2019) found that the primary compounds in liquid smoke from *Durio zibethinus* L., *Garcinia mangostana* Linn., and *Lansium domesticum* Serr. in each case were organic acid, phenols, and methoxyphenols. Phenolic substances like phenol, syringol, guaiacol, xylenol, and cresol, recognized for their biocidal properties, elucidate the antibacterial and antifungal effects of liquid smoke according to Yang et al. (2016). Kartal and co-authors (22) observed that the presence of phenolic compounds in liquid smokes might enhance resistance to decay. They found that the among liquid smokes produced from *Cryptomeria japonica* at pyrolysis (270 and 300°C), only the *C. japonica* liquid smoke generated at 270°C exhibited inhibitory effects on the growth of the Trametes versicolor, at a concentration of 0.1%.

Table 8. Total Acid and Total Phenol Concentrations of Liquid Smoke from *Terminalia catappa*

Pyrolysis Temperature (°C)	Total Acid (%)	Total Phenol (%)
400	4.75 ± 0.02 b	1.67 ± 0.02 a
425	5.08 ± 0.01 c	1.62 ± 0.02 a
450	4.48 ± 0.02 a	1.48 ± 0.02 b

[a] Means (*n* = 4). Values accompanied by distinct letters (a–b) indicate significant differences at a P-value less than 0.05 as determined by Tukey's test

4. CONCLUSION

The RSM optimization indicated that the liquid smoke yield from *T. catappa*, the optimal pyrolysis conditions included a particle size of 3.22 mm and a pyrolysis temperature of 425°C, resulting in a liquid smoke yield of 24.67%. The liquid smoke obtained from *T. catappa* pyrolyzed at 400-450°C resulted in complete growth inhibition of *S. commune* at vinegar concentrations of 2.0-4.0%. The main components in the *T. catappa* liquid smoke were 2-methoxy-phenol, creosol, 4-ethyl-2-methoxy-phenol, and 5-methyl-2-furancarboxaldehyde.

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