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Effect of Wood Vinegar and Adhesive Concentration on Combinations of Particle Board Raw Materials and Resistance to Subterranean Termite Attacks by Using Response Surface Methodology

Nurhaida NURHAIDA[1,†] · Handoko HANDOKO[1] · Yuliati INDRAYANI[1] · Dina SETYAWATI[1] · Marwanto MARWANTO[1] · Hasan Ashari ORAMAHI[1]

ABSTRACT

Products derived from lignocellulose are susceptible to substantial damage from termites. We aimed to evaluate the durability of particleboard treated with wood vinegar, adhesive, and a combination of raw materials for particleboard production. Specifically, we examined the effects of adhesive concentration (X_1), wood vinegar concentration (X_2), and a combination of oil palm trunks and sengon wood sawdust (X_3) on the treatment process. The optimal treatment conditions were predicted using response surface methodology with a three-factor inscribed Box-Behnken design, and the differences in termite attack observation techniques between the no-choice and multiple-choice methods were evaluated. The concentration of adhesive and wood vinegar had a notable impact on the durability of the particleboard against termite attacks. The response surface methodology method predicted that a particle board composition with X_1 (16%), X_2 (15%), and the ratio X_3 (50/50) would exhibit the greatest durability and resistance to termite (*Coptotermes curvignathus*) attacks, with a weight loss test value of 1.10% and a mortality probability of 100%. The particleboard composed of X_1 (12%), X_2 (10%), and the ratio of X_3 (75/25) produced the lowest weight loss value of 2.65% when attacked by termites (*C. curvignathus*). The particleboard consisting of X_1 (14%), X_2 (15%), and the ratio of X_3 (25/75) effectively resisted termite attacks with a weight loss test value of 0.38%. This study showed that wood vinegar can be recommended as a natural biopesticide against *C. curvignathus* attacks on particleboard products.

Keywords: wood vinegar, sengon wood, oil palm trunk, particleboard, subterranean termite

1. INTRODUCTION

Indonesia is one of the countries that produces particle boards for domestic and export purposes (Lee *et al.,* 2022). Particleboard can be used a substitute for solid wood. In 2023, the production of particle board was 202,644.92 m^3 (BPS, 2024), an increase of 121.59% compared with that of 2022, which was 166,654.90 m^3 (BPS, 2023).

The utilization of residual natural fibers from agricul-

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[1] Study Program of Forestry, Faculty of Forestry, Tanjungpura University, Pontianak 78124, Indonesia
[†] Corresponding author: Nurhaida NURHAIDA (e-mail: nurhaida@fahutan.untan.ac.id, https://orcid.org/0009-0007-0253-2763)

tural waste as reinforcement materials and for particleboard applications has been explored, including nipah palm frond (Ghani *et al.,* 2024), tea oil camellia fruit shells (Chaydarreh *et al.,* 2021), sorghum (*Sorghum bicolor*; Sutiawan *et al.,* 2024), kenaf (Wan Nadhari *et al.,* 2024), oil palm trunks (Lubis *et al.,* 2024; Zakaria *et al.,* 2021), bamboo stems (Iswanto *et al.,* 2020), and sengon wood (Karliati *et al.,* 2024; Marwanto *et al.,* 2018). Recently, in Indonesia, there has been a shift toward using fast-growing wood materials for particleboard production in Indonesia, owing to their rapid availability. Among the fast-growing wood species used in the Indonesian timber industry, sengon wood is notable (Karliati *et al.,* 2024; Marwanto *et al.,* 2018). Furthermore, Indonesia and Malaysia are the primary producers of palm oil (Nuryawan *et al.*, 2022), palm waste is produced in the form of oil palm trunks (Pulingam *et al.*, 2022), and oil palm trunk is a potential raw material for particle board (Zakaria *et al.*, 2021). The incorporation of mixed-particle raw materials can enhance the quality of manufactured biocomposites, such as bamboo-oriented strand boards (Maulana *et al.*, 2021).

The limitations of wood-based panels such as particleboard products include low dimensional stability against changes in environmental moisture content and the susceptibility to attacks by wood-destroying insects (Hartono *et al.,* 2023; Lee *et al.,* 2023a). Researchers have successfully attempted to improve the resistance of composite boards to biological attacks treating boards (Lee *et al.,* 2022). Among these treatments is the use of wood vinegar (Arsyad *et al.,* 2019; Sunarti *et al.,* 2014). Research has indicated that the durability of particle board with the addition of wood vinegar from durian fruit peel at concentrations of 10% increased the durability of particle board against termite attacks (Pardosi *et al.,* 2012).

Wood vinegar, including that obtained from various types of wood and biomass (Oramahi *et al.,* 2022b, 2023, 2024), has been used as an antitermitic treatment (Oramahi *et al.,* 2020a; Suprianto *et al.,* 2023) and as an antifungal treatment (Kuswadi *et al.,* 2023; Oramahi *et al.,* 2010).

Wood vinegar obtained from durian wood (*Durio* sp.) exhibited antitermitic properties against *Coptotermes formosanus* Holmgren in a no-choice experiment (Suprianto *et al.,* 2023). Oramahi *et al.* (2024) reported the main components of mabang wood vinegar as 1,2-ethanadiol, acetic acid, phenol, 1-(2-furanyl)-ethanone, 2-propanone, and methyl ester. Additionally, the chemical component in wood vinegar was effective as the antitermitic and antifungal treatments (Oramahi *et al.,* 2023; Suprianto *et al.,* 2023).

Variations in raw material types and pyrolysis temperatures during wood vinegar production influence its characteristics, such as constituent chemicals and yield (Manmeen *et al.*, 2023; Oramahi *et al.,* 2020b, 2023) but increase the number of variables that must be observed to produce the best particleboard. Because of the variety of research variables observed and to avoid insignificant analysis results on the durability of particle boards, response surface methodology (RSM) was used (Eyide *et al.,* 2023).

RSM has been successfully used for the optimization of wood vinegar production (Oramahi *et al.,* 2020b, 2022a, 2024), bioactive chemical components of wood vinegar (Oramahi *et al.,* 2019), and particleboard characteristics (Baskaran *et al.,* 2015; Lee *et al.,* 2023b). However, using RSM increases the number of variables that must be observed to produce the best particleboard. Studies have used durability tests to determine the resistance to termite attacks. Researchers have used natural (Hermawan *et al.*, 2024) and laboratory methods [no choice (Kadir *et al.*, 2022) and multiple-choice (Cosme *et al.*, 2018)] to determine the durability of wood products against termites. Cosme *et al.* (2020) showed that testing wood resistance to *Cryptotermes brevis* attacks had a significant influence on the results.

According to a review of the literature, no study has investigated the durability of particleboards made from a mixture of oil palm trunks and sengon wood sawdust with added wood vinegar and different concentrations of adhesive by using RSM. Thus, the aim of this study was to determine the durability of particleboard against *Coptotermes curvignathus* termites by using two testing methods: no-choice and multiple-choice.

2. MATERIALS and METHODS

2.1. Materials

Oil palm trunks and sengon wood, estimated to be 20 and 10 years old, respectively, were harvested from the Tanjungpura University area and collected from furniture home businesses in Pontianak. Next, the chopped oil palm trunks were allowed to dry for one week in the sun. Finally, the oil palm trunks and sengon wood were ground to a particle size of 2.3 mm, and the sawdust was dried in an oven set at 60℃ to a moisture level of 5%. The wood vinegar was produced from sengon wood (Kuswadi *et al.*, 2023).

2.2. Manufacturing particleboard

A total of 15 single-layer panels with a density of 0.7 g/cm^3 were produced. Three of each combination were made from oil palm and sengon particles: adhesive concentration (urea formaldehydes) was 12%, 14%, and 16%; wood vinegar concentration was 5%, 10%, and 15%; and the ratio of oil palm trunk and sengon wood sawdust was 25:75, 50:50, and 75:25 (Table 1). Hand-formed mats in a 30 cm × 30 cm frame were compressed to a thickness of 1.0 cm. The boards were stored in a room maintained at 26 ± 2℃ and a relative humidity of 70% ± 2% until the moisture content of the boards reached 5%. The particleboard was cut to a length, width, and thickness of 2 × 2 × 1 cm, respectively. The samples were oven-dried at 100℃ until they reached a constant initial weight.

2.3. Testing resistance to subterranean termites

Termite tests were conducted using two methodologies: multiple- and no-choice feeding. Termites (*C. curvignathus* Holmgren subterranean) were collected from the rubber forests of Java Tengah Village, Sungai Ambawang District, and Kubu Raya Regency along with the tree trunks they attacked and brought to the termite house of the Faculty of Forestry, Tanjungpura University. Termite conditioning was performed for one month before the feeding test process was conducted.

The laboratory subterranean termite attack test used in this study was based on Indonesian standards (SNI, 2006). In the no-choice test method, a glass container was used to hold each wood test specimen and 200 g sterilized sand. The sand was moistened with sufficient water to achieve a moisture content of 7%, which is the maximum amount of water the sand can hold. Each

Table 1. Level of variable used for Box-Behnken design

Independent variable	Symbol	Coded variable level		
		Low	Center	High
		−1	0	1
Adhesive concentration (%)	X_1	12	14	16
Wood vinegar concentration (%)	X_2	5	10	15
Ratio of oil palm trunk and sengon wood sawdust	X_3	25:75	50:50	75:25

container was supplemented with 50 healthy and active workers from a laboratory colony of *C. curvignathus*, a Holmgren's subterranean termite.

For the multiple-choice test, five plastic containers with a diameter of 18 cm and height of 5.5 cm were used. Each container was filled with sterile sand as high as ± 1 cm (100 g) and moistened with 20 mL water to maintain humidity. Plastic gauze measuring 16 cm in diameter was placed on top of the sand to prevent direct contact of the sample with the sand. Each treatment sample was allocated to a separate test container, and 200 subterranean termites were introduced into each container, with a worker-to-soldier caste ratio of 180:20. Fig. 1 illustrates the disparity in the positioning of test samples between the no-choice and multiple-choice methods.

The containers were stored for three weeks in a poorly lit room with a temperature of 25℃–30℃ and a relative humidity of 80%–90%. The weight of the sand was monitored every week, and if the moisture content decreased by 2% or more, water was supplied to increase it to the required level. After the exposure period, the particleboard specimens were cleaned and oven-dry weighted at 100℃. The endpoints assessed were particleboard mass loss (mg), termite feeding rate, wood resistance class, termite mortality, particleboard moisture content, and particleboard protection level.

The formulas for calculating the moisture content and percentage of particleboard weight loss were based on those of Thybring (2013).

$$MC = (W1 - W0) / (W0) \times 100\% \quad (1)$$

Where W0 and W1 are oven-dried weight and air-dried weight, respectively, and MC is the moisture content.

$$\text{Termite mortality} = (T1 - T2) / T1 \times 100\% \quad (2)$$

Where T1 is the number of live termites before the test, and T2 is the number of live termites after the test.

$$\text{Particleboard mass loss (mg)} = W3 - W4 \quad (3)$$

Where W3 is the oven-dried weight of the specimen before the test (mg), and W4 is the oven-dried weight of the specimen after the test (mg).

2.4. Response surface methodology design to data analysis

The optimization procedure was designed based on a three-factor inscribed Box-Behnken design (BBD) with independent variables: adhesive concentration was 12%, 14%, and 16%; wood vinegar concentration was 5%, 10%, and 15%; and ratios of oil palm trunk and sengon wood sawdust were 25:75, 50:50, and 75:25. There were three levels of each variable for a total 15 of runs (Table 1).

BBD applied termite mortality (Y_1), weight loss of particleboard for the no-choice test (Y_2), weight loss of particleboard for the multiple-choice test (Y_3) as a function of adhesive concentration (X_1), wood vinegar concentration (X_2), and a ratio of oil palm trunk to sengon wood sawdust (X_3; Table 1). For the RSM

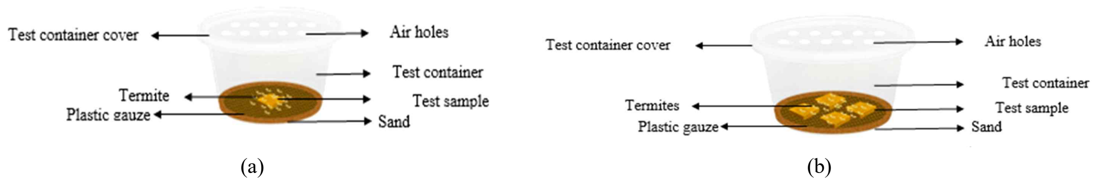


Fig. 1. Termite testing methods. (a) No choice, (b) multiple choice.

design points, these variables were categorized as low, medium, or high. As indicated in the literature, to track how the independent factors affect the response, we conducted an experiment using BBD (Li *et al.,* 2024; Liu *et al.,* 2013).

For optimal point prediction, the second-order polynomial equation was as follows:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \grave{o} \quad (4)$$

Where $\beta_0 \beta_i$, β_{ii}, and β_{ij} are the regression coefficients for the intercept, linear, quadratic, and interaction terms, respectively, and χ_i and χ_j are the independent variables (Sodeifian *et al.,* 2018, 2019).

The analysis of variance for the response of the surface quadratic model and the statistical significance of the influence was analyzed using *F*-tests. The significance of each term was calculated using the *F*-value and Prob > *F*-values, with larger *F*-values indicating that the term was significant (Anderson-Cook *et al.,* 2009; Safari *et al.,* 2018).

3. RESULTS and DISCUSSION

3.1. Design of experiments and analysis of variance

The response correlation was determined using second-order BBD. Table 2 presents the overall responses of the proposed experimental design to termite mortality and particleboard weight loss. To provide all responses with a clear representation of the interactions between variables, we used a quadratic model in software. The variables in response in Equations (5) to (7) were coded values representing termite mortality (Y_1), weight loss of particleboard for the no-choice test (Y_2), and weight loss of particleboard for the multiple-choice test (Y_3) as a function of adhesive concentration (X_1), concentration of wood vinegar (X_2), and ratio of oil palm trunk and sengon wood sawdust (X_3). These equations were derived from the experimental data of the model. The final equations in terms of the coded factors are expressed in Equations (5) to (7).

A second-order BBD was employed to establish relationships between the responses. Table 2 shows the collective responses of the proposed experimental design to termite mortality and particleboard weight loss. Using the aforementioned software, a quadratic model was selected for all the responses to elucidate the interactions among the variables. The response equations derived from the experimental data by using the model are expressed in Equations (5) to (7). The variables in those equations are represented by coded values: termite mortality (Y_1); weight loss of particleboard for the no-choice test (Y_2); and weight loss of particleboard for the multiple-choice test (Y_3) as functions of adhesive concentration (X_1), wood vinegar concentration (X_2), and the ratio of oil palm trunk to sengon wood sawdust (X_3). The final equations in terms of the coded factors are Equations (5) to (7).

Equation for termite mortality

$$(Y_1) = 90.00 + 2.15X_1 - 5.96X_2 + 0.465X_3 + 8.32X_1.X_2 - 3.37X_1.X_3 - 0.026X_2.X_3 - 10.11X_1^2 - 9.90X_2^2 + 0.47X_3^2 \quad (5)$$

Equation for weight loss of particle board for no-choice

$$(Y_2) = 2.39 + 0.05X_1 - 0.198X_2 + 0.595X_3 + 0.015X_1.X_2 + 0.16X_1.X_3 - 0.215X_2.X_3 - 0.698X_1^2 - 0.428X_2^2 + 0.048X_3^2 \quad (6)$$

Equation for weight loss of particle board for multiple-choice

Table 2. Experiment design for termite mortality of particleboard and weigh loss of particleboard for choice test and multiple-choice test as comparison of actual and predicted responses

Run	Variable			Response					
	X_1	X_2	X_3	Y_1		Y_2		Y_3	
				A	P	A	P	A	P
1	−1	−1	0	1.46	2.78	1.71	1.20	66.61	98.14
2	−1	1	0	1.17	2.41	0.53	1.15	65.21	90.81
3	1	−1	0	1.33	3.02	0.61	0.43	58.13	115.61
4	1	1	0	1.10	2.39	0.71	0.72	90.00	90.00
5	−1	0	−1	1.15	2.39	0.70	0.72	79.98	90.00
6	−1	0	1	2.03	2.07	2.65	0.55	76.49	109.68
7	1	0	−1	1.13	2.39	0.79	0.72	73.70	90.00
8	1	0	1	2.65	1.12	1.72	0.53	83.68	85.58
9	0	−1	−1	1.47	3.16	0.60	2.05	75.04	106.31
10	0	−1	1	3.08	1.72	1.23	0.79	73.70	99,69
11	0	1	−1	1.37	2.02	0.38	1.58	83.68	83.47
12	0	1	1	2.12	3.51	1.13	0.34	82.25	107.99
13	0	0	0	2.88	3.08	0.46	0.86	90.00	89.08
14	0	0	0	2.17	1.49	0.98	−0.56	90.00	100.07
15	0	0	0	2.12	1.99	0.72	0.48	90.00	85.29

X_1, adhesive concentration (%); X_2, wood vinegar concentration (%); X_3, ratio of oil palm trunk and Sengon wood sawdust; Y_1, weight loss of particle board in the no-choice test; Y_2, weight loss of particle board in the multiple-choice test; Y_3, termite mortality; A, actual value (actual value in Y_3 is data transformation with Excel in formula = DEGREES (ASIN((data actual/100)^0,5)); and P is the prediction value with response surface methodology.

$$(Y_3) = 0.72 - 0.22X_1 - 0.175X_2 + 0.533X_3 + 0.32X_1.X_2 - 0.255X_1.X_3 + 0.03X_2.X_3 + 0.40X_1^2 - 0.23X_2^2 + 0.345X_3^2 \quad (7)$$

These equations were used to calculate the actual and expected values from the experimental results. The suitability of the Box-Behnken model was tested, and its quality was assessed using analysis of variance. Additionally, it was used to estimate the effects of adhesive concentration (X_1), wood vinegar concentration (X_2), the ratio of oil palm trunk to sengon wood sawdust (X_3), and their interactions with the responses as a function of termite mortality (Y_1), as well as the weight loss of the particleboard for samples that had no choice (Y_2) or multiple choices (Y_3). Tables 3–5 display the regressions of the coefficients, model significance, and lack of fit, all of which were computed using statistical software.

The overall model fit was assessed using the coefficient of determination (R^2). A model is deemed ideal when the R^2 values are closer to 1, owing to this leading to better response prediction (Arabi *et al.,* 2023). Tables 3–5 further show that the weight loss of the particleboard for the multiple-choice and termite mortality tests had R^2 values of 0.924, 0.908, and 0.955, respectively.

Table 3. Analysis of variance (ANOVA) for fitted models for weight loss of particle board in no-choice test

Source	Sum of squares	*df*	Mean square	*F*-value	*p*-value	
Model	5.83	9	0.6477	6.77	0.0243	Significant
X_1	0.02	1	0.02	0.2092	0.6666	
X_2	0.312	1	0.312	3.26	0.1306	
X_3	2.83	1	2.83	29.62	0.0028	
$X_1.X_2$	0.0009	1	0.0009	0.0094	0.9265	
$X_1.X_3$	0.1024	1	0.1024	1.07	0.3482	
$X_2.X_3$	0.1849	1	0.1849	1.93	0.2231	
X_1^2	1.8	1	1.8	18.79	0.0075	
X_2^2	0.6748	1	0.6748	7.06	0.0451	
X_3^2	0.0083	1	0.0083	0.0871	0.7797	
Residual	0.478	5	0.0956			
Lack of fit	0.1166	3	0.0389	0.2152	0.8795	Not significant
Pure error	0.3614	2	0.1807			
Cor total	6.31	14				

R^2 = 0.924, adjusted R^2 = 0.789, predicted R^2 = −0.575, adequate precision = 7.98, SD = 0.309, coefficient of variation = 17.03, mean = 1.82.
X_1, adhesive concentration (%), X_2, wood vinegar concentrations (%) and X_3, ratio of oil palm trunk and sengon wood sawdust.

Based on the provided R^2 values, we inferred that the fitted model only failed to explain 7.6% of the total variables for termite mortality, 9.2% for particleboard weight loss in the no-choice test, and 4.5% for particleboard weight loss in the multiple-choice test. The response R^2 values were close to 1. For all replies (Table 5), the adjusted R^2 and projected R^2 were generally in reasonable agreement.

3.2. Weight loss of particleboard based on no-choice and multiple-choice methods

The weight loss of particleboard owing to termite attacks by using the no-choice method ranged from 1.10% to 3.08% (Fig. 2). The highest weight loss was in particleboard, which had a composition of X_1 (14%), X_2 (5%), and a ratio of X_3 (75/25). The smallest weight loss in particleboard was in particleboard with a composition of X_1 (16%), X_2 (15%), and a ratio of X_3 (50/50). Detailed data are shown in Table 2, where part of response Y_1 is in the actual value (A). Data analysis to obtain optimal conditions for particleboard by using software (Design Expert, Stat-Ease, Minneapolis, MN, USA) with RSM, particularly with BBD presenting response surface plots in the form of surface and contour plots (three-dimensional, 3D), is capable of interpreting variable interactions and is highly informative (Adiyanto *et al.,* 2023).

According to Baskaran *et al.* (2015), 3D response surface plots are informative and can be used to analyze how these factors interact. As shown in Fig. 3, the surface and contour plots of particleboard weight loss in the no-choice method illustrated the influence of varia-

Table 4. Analysis of variance (ANOVA) for fitted models for weight loss of particle board in multiple choice

Source	Sum of squares	*df*	Mean square	*F*-value	*p*-value	
Model	4.83	9	0.5367	5.53	0.0371	Significant
X_1	0.388	1	0.388	4	0.102	
X_2	0.2444	1	0.2444	2.52	0.1733	
X_3	2.26	1	2.26	23.31	0.0048	
$X_1.X_2$	0.4096	1	0.4096	4.22	0.0951	
$X_1.X_3$	0.2572	1	0.2572	2.65	0.1644	
$X_2.X_3$	0.0032	1	0.0032	0.0334	0.8621	
X_1^2	0.5912	1	0.5912	6.09	0.0566	
X_2^2	0.1956	1	0.1956	2.02	0.2149	
X_3^2	0.4485	1	0.4485	4.62	0.0842	
Residual	0.4851	5	0.097			
Lack of fit	0.3502	3	0.1167	1.73	0.3867	Not significant
Pure error	0.1349	2	0.0675			
Cor total	5.32	14				

R^2 = 0.908, adjusted R^2 = 0.742, predicted R^2 = −0.128, adequate precision = 9.30, SD = 0.313, coefficient of variation = 31.46, mean = 0.995.
X_1, adhesive concentration (%), X_2, wood vinegar concentrations (%) and X_3, ratio of oil palm trunk and sengon wood sawdust.

bles X_1 and X_2, indicating optimum conditions at X_1 (14%) and X_2 (10%), with a particleboard weight loss value of 2.88%. Additionally, the influence of variables between X_1 and the ratio of X_3 on no-choice method for weight loss particleboard is illustrated in Fig. 4, showing optimum conditions at X_1 (14%) and the ratio of X_3 (50/50) with a particleboard weight loss of 2.88%. As shown in Fig. 5, interaction between X_2 and the ratio of X_3 indicated optimum conditions with X_2 (15%) and the ratio of X_3 (75/25) with a particleboard weight loss of 2.88%.

The multiple-choice method showed the weight loss due to termite attacks on particle boards and the effect of the research treatments. The multiple-choice method's weight loss average was between 0.38% and 2.65% (Fig. 6). The lowest weight loss value was for particleboard, which had a composition of X_1 (14%), X_2 (15%), and a ratio of X_3 (25/75). The highest weight loss value was for particleboard, which had a composition of X_1 (12%), X_2 (10%), and a ratio of X_3 (75/25). Detailed data are shown in Table 2 for response Y_2 in the actual value (A).

The addition of wood vinegar to particleboard has also been shown to increase its durability. The addition of wood vinegar from empty oil palm fruit bunches to particleboard has been shown to increase its durability. Our research results indicated that the addition of wood vinegar at concentrations of 5% and 10% increased the durability of the particle boards against termite attacks (Sunarti *et al.,* 2014).

An illustration of the contour and surface response surfaces in Fig. 7 shows the interaction of X_1 and X_2 with weight loss in the multiple-choice method. The optimal conditions for particleboard were X_1 (14%) and

Table 5. Analysis of variance (ANOVA) for fitted models for termite mortality

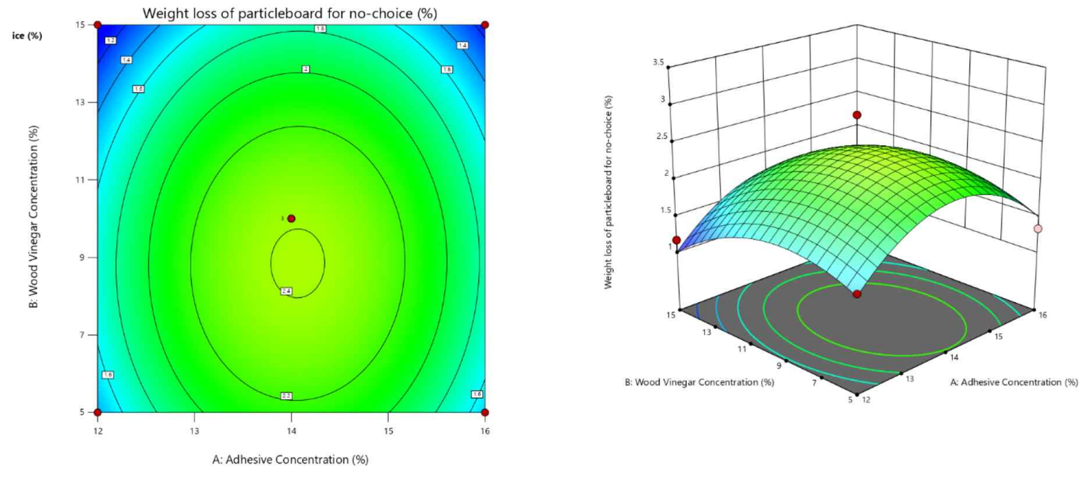
Source	Sum of squares	*df*	Mean square	*F*-value	*p*-value	
Model	1,331.47	9	147.94	11.85	0.0071	Significant
X_1	37.07	1	37.07	2.97	0.1454	
X_2	283.93	1	283.93	22.75	0.005	
X_3	1.73	1	1.73	0.1386	0.7249	
$X_1.X_2$	276.72	1	276.72	22.17	0.0053	
$X_1.X_3$	45.36	1	45.36	3.63	0.1149	
$X_2.X_3$	0.002	1	0.002	0.0002	0.9903	
X_1^2	377.31	1	377.31	30.23	0.0027	
X_2^2	362.16	1	362.16	29.02	0.003	
X_3^2	7.54	1	7.54	0.6039	0.4723	
Residual	62.41	5	12.48			
Lack of fit	62.41	3	20.8			
Pure error	0	2	0			
Cor total	1,393.88	14				

R^2 = 0.955, adjusted R^2 = 0.875, predicted R^2 = −0.284, adequate precision = 11.14, SD = 3.53, coefficient of variation = 4.50, and mean = 78.56.
X_1, adhesive concentration (%); X_2, wood vinegar concentration (%); and X_3, ratio of oil palm trunk to Sengon wood sawdust.

(a) (b)

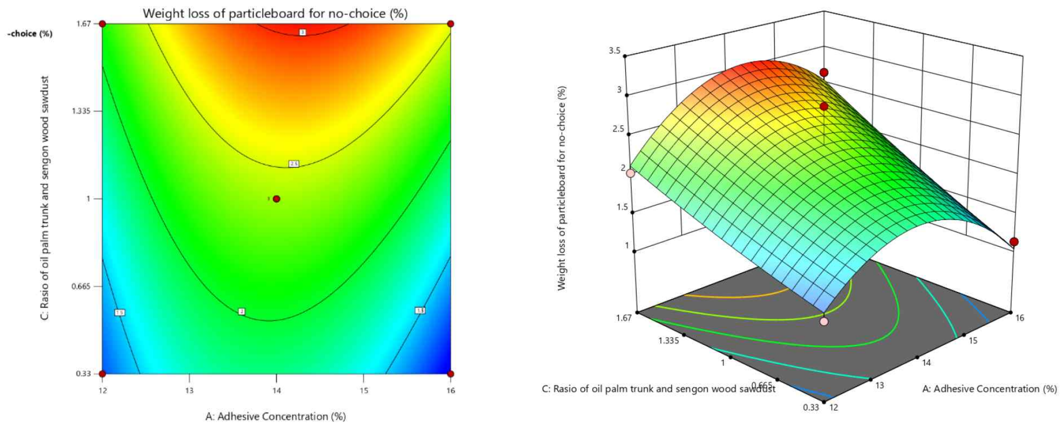
Fig. 2. Particleboard no-choice weight loss. Lowest (a), highest (b).

X_2 (10%), with a weight loss value of 0.46%. Fig. 8 shows the interaction between X_1 and the ratio of X_3 under the optimum conditions of X_1 (14%) and the ratio of X_3 (50/50) with a weight loss value of 0.46%. The plot shows that increasing the concentration of wood vinegar provided maximum resistance to subterranean termite (*C. curvignathus*) attacks. Fig. 9 shows the interaction between X_2 and the ratio of X_3 under the optimum conditions of X_2 (10%) and the ratio of X_3 (50/50) with a weight loss value of particleboard multi-



(a) (b)

Fig. 3. Response surface (a) and contour plots (b) for effects of adhesive concentration (X_1) and wood vinegar concentration (X_2) on weight loss of particleboard at no choice method.

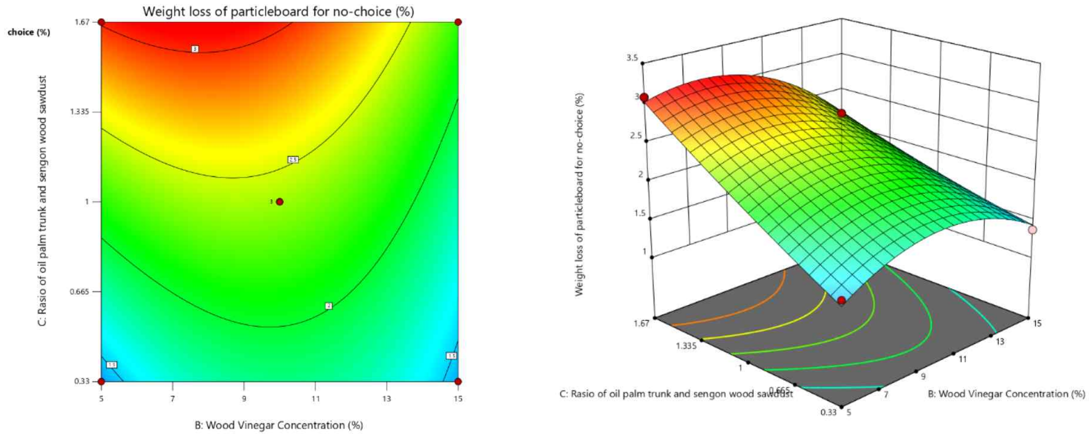


(a) (b)

Fig. 4. Response surface (a) and contour plots (b) for effects of adhesive concentration (X_1) and ratio of oil palm trunk and sengon wood sawdust (X_3) on weight loss of particleboard at no-choice method.

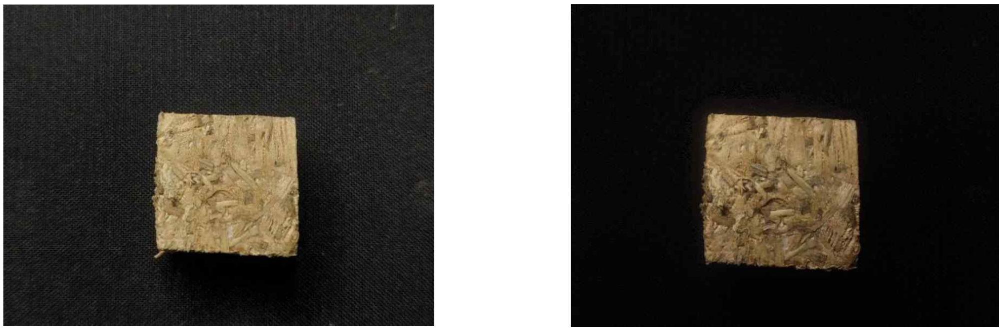
ple-choice testing of 0.46%.

Based on the weight loss value of the particle board obtained from the test, the average weight loss value in the no-choice and multiple-choice methods ranged from 1.10% to 3.08% and 0.38% to 2.65%, respectively. Based on the particle board durability level classification in the SNI 01-7207 2006 standard (SNI, 2006), the particleboard was in a very durable category (durable class I). This showed that all research treatments affected the durability of the resulting particleboard. RSM demonstrated that the higher concentration of wood vinegar and adhesive increased the resistance of particle



(a) (b)

Fig. 5. Response surface (a) and contour plots (b) for effects of wood vinegar concentrations (X_2) and ratio of oil palm trunk and sengon wood sawdust (X_3) on weight loss of particleboard at no-choice method.



(a) (b)

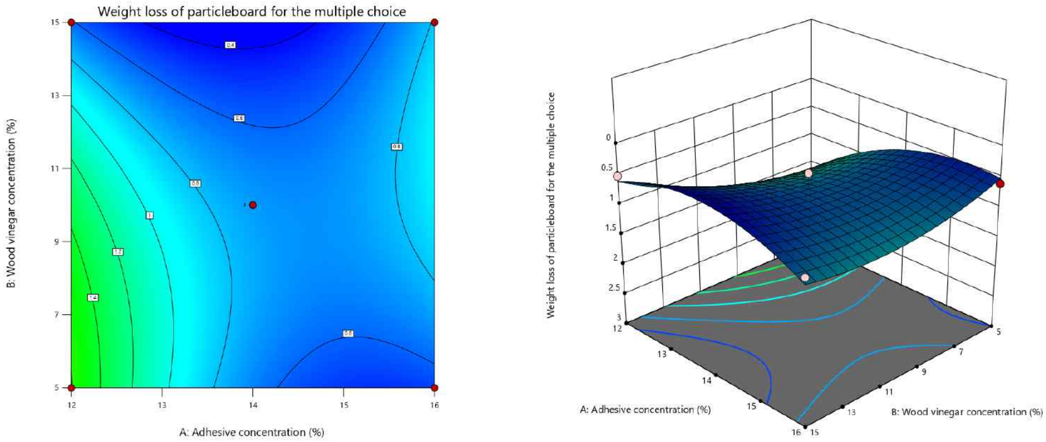
Fig. 6. Weight loss of particle board by multiple-choice method. Lowest (a), highest (b).

board to termite attacks, using the no-choice method and the multiple-choice method. This finding supports that of Arsyad *et al.* (2019), who found that wood vinegar can be used to increase the durability of wood against termite attacks.

Observation of termite feeding behavior by using the no-choice and multiple-choice methods was also conducted by Cosme *et al.* (2018, 2020). The results showed that in general, the durability of the tested samples exhibited the same phenomenon. However, when using the multiple-choice method, the preference for the consumption of certain woods was increasingly visible, illustrating that termites tend to consume wood with low durability (Cosme *et al.*, 2018, 2020).

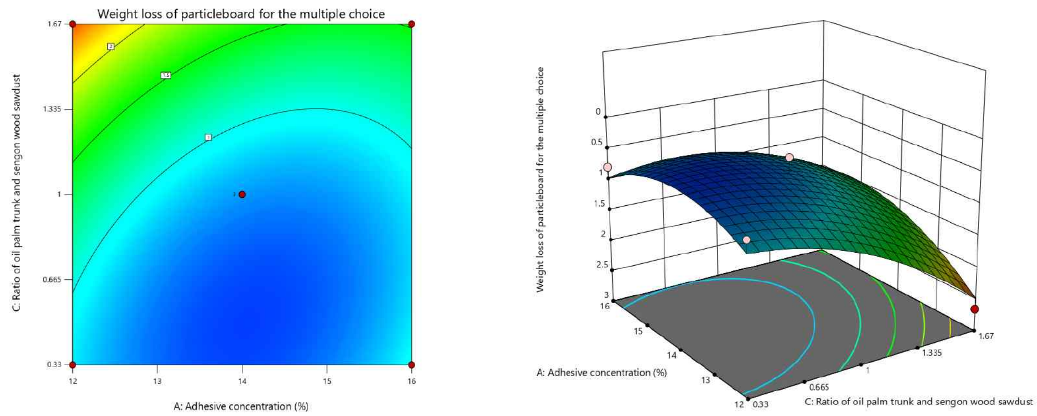
3.3. Termite mortality

Mortality values ranged from 58.13% to 90.00%, with the lowest mortality percentage in particleboards with X_1 (16%), X_2 (5%), and the ratio of X_3 (50/50). Additio-



(a) (b)

Fig. 7. Contour (a) and surface (b) optimum conditions of particle board as a function of adhesive (X_1) and wood vinegar (X_2) on weight loss of particleboard at multiple-choice method.

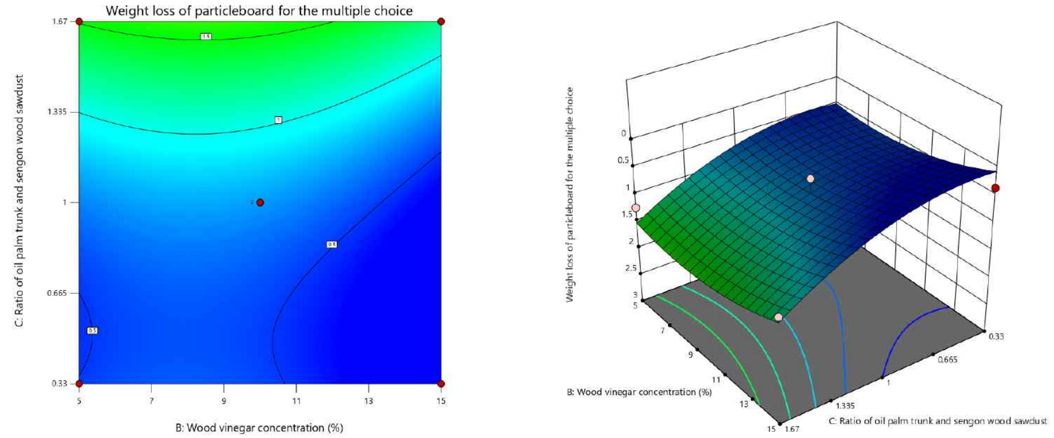


(a) (b)

Fig. 8. Contour (a) and surface (b) optimum conditions of particle board as a function of adhesive (X_1) and ratio of oil palm trunks and sengon (X_3) on weight loss of particleboard at multiple-choice method.

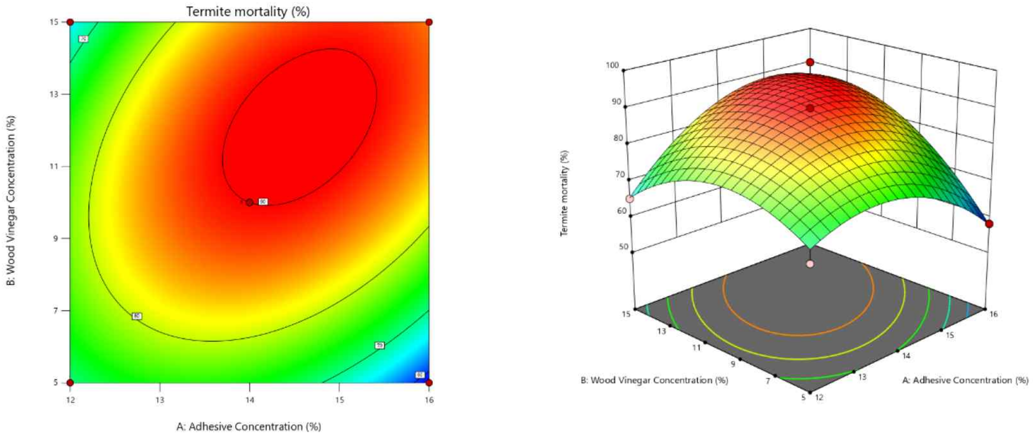
nally, the highest mortality value was in particleboard with a composition of X_1 (16%), X_2 (15%) and a ratio of X_3 (50/50), which was 90%. Detailed data are shown in Table 2 for response Y_3 in the actual value (A). The impact of the interaction between the adhesive concentration (X_1), wood vinegar concentration (X_2), and various ratios of oil palm trunk and sengon wood sawdust (X_3) on termite mortality after exposure to particleboard is shown in the response surface 3D plots in Figs. 10−12. Both responses exhibited a quadratic trend with respect to the experimental variables [Figs. 10(b), 11(b), and 12(b)].

This study showed that a higher concentration of wood vinegar can increase the durability of particle-



(a) (b)

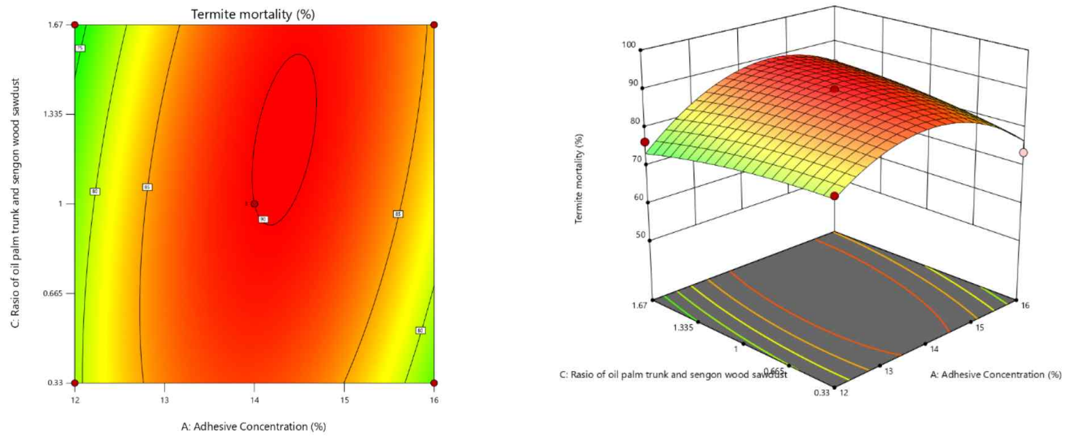
Fig. 9. Contour (a) and surface (b) optimum conditions of particle board as a function of wood vinegar (X_2) and the ratio of oil palm trunk and sengon wood sawdust (X_3) on weight loss of particleboard at multiple-choice method.



(a) (b)

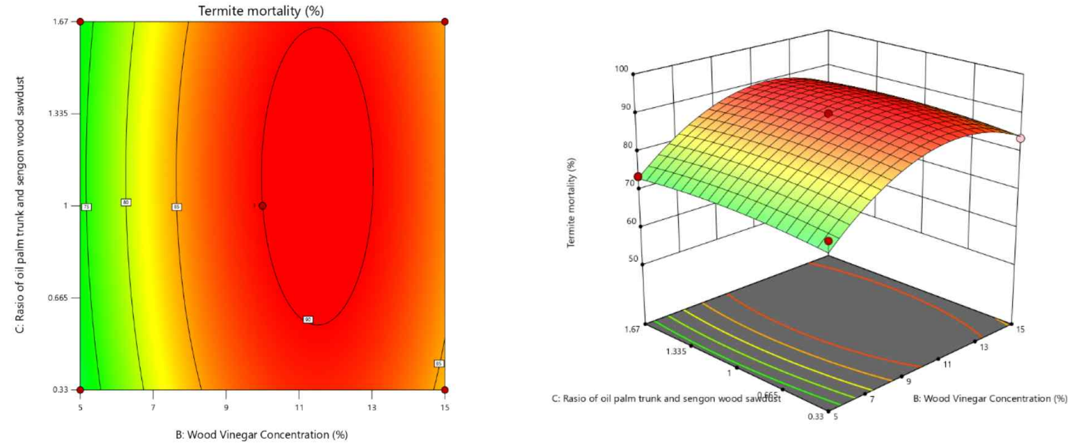
Fig. 10. Response surface (a) and contour plots (b) for effects of adhesive concentration (X_1) and wood vinegar concentration (X_2) on termite mortality.

board. The acid, phenol, and carbonyl components of wood vinegar are toxic to termites and wood-rotting fungi (Oramahi *et al.,* 2022b; Suprianto *et al.,* 2023). Furthermore, increasing particle board hardness due to increasing adhesive concentration caused termite feeding ability to decrease. The hardness of the particleboard might have been caused by an increase in the number of glue lines owing to the increased adhesive concentration. This phenomenon was also reported by Cosme *et al.* (2018), who showed that the harder the wood, the greater the decrease in the termite feeding ability. This could have been caused by a decrease in the number of



(a) (b)

Fig. 11. Response surface (a) and contour plots (b) for effects of adhesive concentration (X_1) and ratio of oil palm trunk and sengon wood sawdust (X_3) on termite mortality.



(a) (b)

Fig. 12. Response surface (a) and contour plots (b) for effects of wood vinegar concentration (X_2) and ratio of oil palm trunk and sengon wood sawdust (X_3) on termite mortality.

wood pores. Furthermore, the differences in the raw materials used affect the ability of termites to consume wood products. Cosme *et al.* (2020) showed that the level of termite consumption depended on the chemical components of the wood.

3.4. Optimum condition

The RSM method was used to determine the durability of particleboard against termite attacks by using several research treatments. The RSM showed that increasing the concentrations of adhesive and wood vinegar affected termite mortality significantly. In line with Adfa *et al.* (2017) and Kadir *et al.* (2022), in this study, wood vinegar increased the resistance of wood to termite attacks. Other studies have shown that wood vinegar tested using the termite-repellent method on Whatman paper with *C. formosanus* (Oramahi and Yoshimura, 2013) and *C. curvignathus* (Oramahi *et al.*, 2022b) also acted as biocides. Fig. 10 shows the termite mortality contour and surface, illustrating the effect of variables X_1 and X_2, the optimum conditions at X_1 (14%) and X_2 (10%). Increasing the concentration of the adhesive and wood vinegar resulted in a high mortality rate. The interaction between X_1 and the ratio of X_3 (Fig. 11) showed the optimum condition of X_1 (14%) and the ratio of X_3 (50/50), with a mortality value of 90%. The interaction between X_2 and the ratio of X_3 based on the contour and surface in Fig. 12 showed the optimum conditions for X_2 (10%) and the ratio of X_3 (50/50). The contour and surface response surface plots (3D) of the three images produced provided the same optimum results for all factors used with the combination of X_1 (14%), X_2 (10%), and the ratio of X_3 (50/50), with a termite mortality value of 90%.

All contours and surfaces (3D) on the response surface plot interpreted the interaction between variables, showing the effect of the interaction between adhesive and wood vinegar, adhesive and the ratio of oil palm trunks to sengon wood composition, and wood vinegar and the ratio of oil palm trunks to sengon wood composition on particleboard resistance from subterranean termite (*C. curvignathus*) attacks and termite mortality. Based on the values given by the software using the RSM method to achieve optimum conditions for particle board durability against termite attacks, we recommend that the composition used be the concentration of adhesive, wood vinegar, and a ratio of oil palm trunks-sengon wood sawdust of 16%, 10%, and 25/75, respectively. The particle board composition produced the lowest weight losses in the no-choice and multiple-choice methods of 1.04% and 0.97%, respectively. Its composition was predicted to have a termite mortality rate of 76.78%.

4. CONCLUSIONS

This study attempted to predict the optimum conditions for particleboard durability against subterranean termite (*C. curvignathus*) attacks by using the RSM method in several research treatments: adhesive concentration, wood vinegar, and a combination of oil palm trunks and sengon wood. Particle board with a composition of 14% adhesive content, 5% wood vinegar, and a ratio of 75/25 oil palm trunks-sengon wood had the lowest resistance to subterranean termite (*C. curvignathus*) attacks in the no-choice test, with a weight loss test value of 3.08%. Particle board with a composition of 16% adhesive content, 15% wood vinegar, and a ratio of 50/50 oil palm trunks-sengon wood had the highest resistance to termite (*C. curvignathus*) attacks, with a weight loss test value of 1.10% and a mortality of 100%. Multiple-choice testing of particleboard with 12% adhesive content, 10% wood vinegar, and a 75/25 ratio of oil palm trunks-sengon wood had the lowest resistance to subterranean termite attacks (*C. curvignathus*), with a weight loss value of 2.65%. Particleboard with a composition of 14% adhesive content, 15% wood vinegar, and a ratio of 25/75 oil palm trunks-sengon wood had the highest resistance to termite attacks (*C. curvignathus*), with a weight loss test value of 0.38%.

Based on the calculation simulation by using the RSM method, the optimal results for the durability of particleboard from a combination of oil palm trunks-sengon wood with the addition of wood vinegar were 16% adhesive, 10% wood vinegar, and a ratio of 25/75 oil palm trunk–sengon wood. The higher the urea formaldehyde adhesive content and concentration of wood vinegar, the greater the durability of the produced particleboard.

CONFLICT of INTEREST

No potential conflict of interest relevant to this article was reported.

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