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RESEARCH ARTICLE

Balancing Mechanical Integrity and Sound-Damping Performance of Water Hyacinth-Reinforced Unsaturated Polyester Composites for Coastal Food-Processing Facilities

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ABSTRACT

Unsaturated polyester (UP)/water hyacinth (WH) composites were developed as sound-damping panels for pump houses and coastal food-processing facilities. A Box-Behnken design was employed to optimize WH content (30-60 wt%), NaOH concentration (5-10 wt%), and alkali treatment duration (2-8 h), with flexural modulus, flexural strength, and noise level reduction as responses. Increasing WH content improved sound attenuation but led to a significant decrease in flexural properties due to limited filler-matrix interfacial adhesion and inefficient stress transfer, as confirmed by scanning electron microscopy. Optimal mechanical performance was achieved at low alkali severity (5 wt% NaOH, 2 h) with 30 wt% WH, yielding a flexural modulus of 4810 MPa and strength of 44 MPa, meeting the Indonesian standard for wood composites. At higher WH loading (60 wt%), noise reduction increased up to 4%, accompanied by severe mechanical degradation. This study demonstrates a trade-off between acoustic functionality and mechanical integrity in UP/WH composites and provides an optimized formulation window for non-structural noise-control applications in water-exposed environments.

Keywords: *water hyacinth, sound damping, flexural, composites, Box-Behnken, SEM*

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INTRODUCTION

Rising sea levels and increased rainfall have intensified flooding risks in many coastal countries, including Indonesia. This problem is often exacerbated by the proliferation of invasive aquatic plants such as water hyacinth (Eichhornia crassipes), which grows rapidly, obstructs waterways, and restricts water flow [1], [2], [3], [4] Mechanical pumping systems are therefore widely used to mitigate flooding by transferring excess water from urban or industrial zones to rivers or coastal outlets. However, continuous pump operation generates substantial low-frequency noise, contributing to noise pollution in surrounding residential and industrial areas [5] Prolonged exposure to such noise has been reported to adversely affect human health and

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workplace comfort, particularly in coastal food-processing facilities where pumps operate near production areas.

Sound-damping panels and acoustic barriers are commonly employed to reduce noise transmission from machinery [5], [6]. Conventional sound-absorbing materials typically rely on perforated panels or porous fillers bonded with polymeric matrices such as epoxy, polyurethane, or unsaturated polyester (UP) [7][8]. Among these, UP is attractive for coastal and food-industry environments due to its relatively low cost, corrosion resistance, ease of processing, and adequate mechanical performance under humid conditions [9], [10]. It is also commonly used as a binder in thermoset composite material such as for building materials, transportation and aerospace, whereas mechanical, fire and wear resistance considered as crucial properties [11], [12], [13], [14]. Therefore, incorporating porous natural materials into UP matrices is a potential strategy to enhance acoustic damping of the composite for non-structural material, while reducing material cost and environmental footprint [15], [16]

Among porous natural material, water hyacinth (WH) is considered as a potential renewable and low-cost filler for sound-absorbing applications due to its naturally porous structure. Several studies have explored WH-based composites using binders such as gypsum, cement, epoxy, and polyvinyl alcohol (PVA), reporting promising sound absorption behaviour [10], [16], [17], [18]. Nevertheless, many of these systems leave WH fibers partially exposed, making them vulnerable to moisture uptake and degradation, which limits their applicability in water-surrounded or high-humidity environments such as pump houses and coastal food-processing facilities. Direct incorporation of WH into thermoset matrices such as UP offers a potential solution by fully encapsulating the filler, thereby improving moisture resistance and durability.

Previous studies on UP/WH composites have primarily focused either on acoustic performance or mechanical behaviour, but rarely addressed both aspects simultaneously. Some reports demonstrated noise reduction using WH-filled polyester panels without examining fiber treatment or mechanical integrity [17], while others investigated alkali-treated WH reinforcements focusing solely on tensile or flexural properties [19], [20]. Moreover, although alkali treatment using sodium hydroxide (NaOH) is known to modify the surface chemistry of natural fibers by partially removing lignin and hemicellulose, excessive treatment can damage cellulose structures and weaken fiber integrity[21]. The combined effects of WH content, NaOH concentration, and treatment duration on both mechanical performance and sound-damping behaviour of UP/WH composites remain insufficiently understood.

One critical challenge in designing WH-based sound-damping composites is balancing acoustic functionality with mechanical integrity [7], [8], [22]. Increasing WH content generally enhances sound attenuation due to increased porosity and internal energy dissipation within the filler structure [16], [18]; however, high filler loading often leads to poor matrix wetting, reduced interfacial adhesion, and inefficient stress transfer, resulting in significant losses in flexural strength and stiffness [9], [19], [23]. Therefore, systematic optimization, such as response surface methodology [12], [24], [25], [26], [12, 21, 23-26], of filler content and treatment conditions is essential to identify a practical formulation window that satisfies both acoustic and mechanical requirements for non-structural applications.

In this study, a Box-Behnken experimental design was employed to statistically evaluate and optimize the effects of WH content (30-60 wt%), NaOH concentration (5-10 wt%), and alkali treatment duration (2-8 h) on the flexural modulus, flexural strength, and sound-damping performance of UP/WH composites. Unlike prior works, this study integrates mechanical characterization, acoustic screening, and morphological analysis to elucidate the trade-off between sound attenuation and mechanical performance. The findings aim to establish an optimized composite formulation suitable for noise-control panels in pump houses and coastal food-processing environments, where durability, moisture resistance, and acoustic functionality are simultaneously required.

METHODS AND ANALYSIS

Unsaturated polyester (UP) resin (Yukalac 157 BQTN-EX; density ≈ 1.2 g cm^{-3}), a pre-accelerated, non-wax, Ortho phthalic polyester suitable for compression molding, was supplied by Justus Kimiaraya (Jakarta, Indonesia). Methyl ethyl ketone peroxide (MEKP) was used as the

curing catalyst. Water hyacinth (WH, Eichhornia crassipes) was collected from waterways near Tangerang, West Java, Indonesia. All materials were used as received unless otherwise specified.

Alkali treatment of water hyacinth

The WH, shown in Figure 1, was subjected to alkali treatment using aqueous sodium hydroxide (NaOH) solutions according to the experimental matrix generated by the Box-Behnken design (BBD). BBD was selected due to its efficiency in evaluating quadratic effects and factor interactions while minimizing the number of experimental runs. Three replicated center-point runs (Runs 3-5) were included at 45 wt% WH, 7.5 wt% NaOH, and 5 h treatment duration to assess experimental repeatability and estimate pure error. No experiments were conducted at extreme combinations (high-high-high or low-low-low), consistent with BBD assumptions [14], [21], [27], [28].

The variable combinations were generated by Minitab software and summarized in Table 1. NaOH concentration (5-10 wt%) and treatment duration (2-8 h) were selected based on reported effective ranges for natural fiber surface modification and preliminary trials [9], [20], [23], [29]. After immersion, the WH were thoroughly washed with distilled water until neutral pH was reached, followed by oven drying for 1 hour. The dried WH was mechanically crushed and sieved to obtain particles below 1 mm. Because quantitative particle-size analysis was not performed, the particle size is reported based on the sieve cutoff rather than as a measured mean particle size and standard deviation. the minimum WH content was set 30% since the aim of this study to utilize maximum in which problematic for surrounding area, while the maximum was expected to be used as high as possible. It was also expected that the more WH, the more noise level was absorbed [17]. However, preliminary trial showed that the WH content more than 60% resulted poor adhesion between UP and WH, so the maximum percentage of WH was set at 60%.

Composite preparations

Composite preparation is summarized in Figure 2. The UP resin was first mixed with 1.5 wt% MEKP catalyst (relative to resin weight) under mechanical stirring. Alkali-treated WH was then gradually incorporated into the resin mixture and stirred at 480 rpm for 5 min using an overhead mechanical stirrer to achieve homogeneous dispersion while avoiding premature curing. The resulting mixture was molded using a compression molding process at 75 °C and 5 bar for 20 min, followed by cooling at 30 °C and 1 bar for 10 min. Circular panels with a diameter of 14 cm were obtained for subsequent characterization.



Figure 1. Alkali treatment of water hyacinth

Characterizations

Flexural properties were evaluated using a Shimadzu AGX-plus universal testing machine in accordance with ASTM D790. The specimen thickness ranged from 3.00 to 4.81 mm (3.98 ± 0.52 mm). The crosshead speed was selected individually according to the specimen thickness in accordance with ASTM D790 rather than using a fixed speed for all specimens, resulted crosshead rate ranging from 1.28 to 2.05 mm/min. Five specimens (n = 5) were tested for each formulation, and the average values were reported.

Sound-damping performance was assessed using a custom-built acoustic setup designed for preliminary low-frequency screening as shown in Figure 3. Although standardized methods such as ISO 354 or ASTM C423 provide full sound absorption characterization, the present setup was designed for comparative low-frequency screening relevant to pump noise. A continuous sound

signal at 100 Hz was generated using a loudspeaker positioned 5 cm from the exterior wall of a climatic room, simulating low-frequency noise typically produced by water pumps. The sound propagated through a cylindrical opening (12 cm diameter, 15 cm thickness), where composite panels were placed. Sound pressure levels were measured using a calibrated sound level meter positioned 5 cm inside the opposite wall. Sound level measurements were repeated three times for each panel (n = 3), and the mean values are reported. This setup was intended to provide comparative sound-damping behavior rather than absolute absorption coefficients.



Figure 2. Composite preparation procedure

The fracture surfaces of selected composite samples were examined using scanning electron microscopy (SEM) to evaluate filler dispersion, interfacial adhesion, and fracture features. Samples representing low, medium, and high WH contents were selected to correlate morphology with mechanical performance. SEM images were acquired under 20 kV accelerating voltage. Working distance was set at 24 for sample with 30 and 60% of fibres, while 31 for that of 45% of fibre due to differences in sample thickness affecting the focus of the samples. Representative regions showing filler dispersion, agglomeration, interfacial debonding, voids, and unembedded filler were identified in the micrographs.

Table 1. Conditions of fibre treatment and composition used in composite preparation.

Run	WH [%]	Fibre Treatment		Run	WH [%]	Fibre Treatment	
		NaOH [%]	Duration [hr]			NaOH [%]	Duration [hr]
Control	0	0	0	8	45	10.0	2
1	45	10.0	8	9	45	5.0	8
2	30	10.0	5	10	60	7.5	8
3	45	7.5	5	11	45	5.0	2
4	45	7.5	5	12	60	5.0	5
5	45	7.5	5	13	60	7.5	2
6	30	5.0	5	14	30	7.5	2
7	60	10.0	5	15	30	7.5	8

Statistical Analysis

Experimental data of the flexural modulus and strength were plotted using polynomial equations as follow :

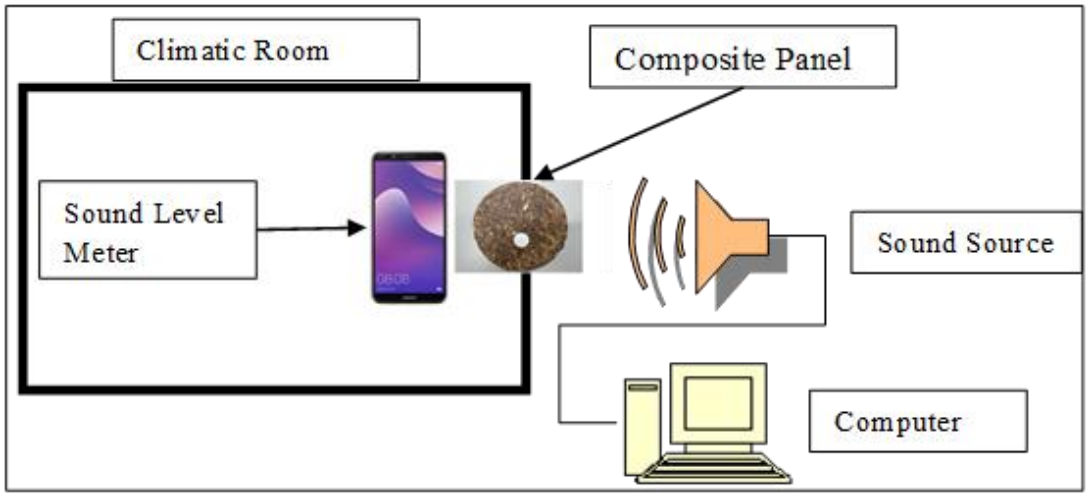
$$y = \beta_0 + \Sigma\, \beta_i\, x_i + \Sigma\, \beta_{ii}\, x_i^2 + \Sigma\, \beta_{ij} x_i x_j \quad (1)$$

where y is the response of the model, x_i and x_j are independent variables, and β_o, β_i, β_{ii} and β_{ij} are coefficients for constants, linear, quadratic, and interactions variables, respectively. Model resulted the highest R^2 were chosen. The optimum conditions are calculated with target 2000 and 20 MPa of flexural modulus and strength, respectively, according to SNI 8154: 2015 - Indonesian Nasional Standard for Wood Composites. Optimizations were done by considering 2 (two) options, namely:

a. Maximize the use of water hyacinth (WH) fibers up to 60% to help reduce environmental waste and promote sustainable utilization of WH,

b. Minimize alkali treatment conditions by optimizing for the shortest processing time and the least amount of chemical use, ensuring a more efficient and environmentally friendly treatment process.

The optimum flexural modulus and strength samples were then tested for sound level measurement.



(a)



(b)



(c)

Figure 3. (a) schematic of sound damping measurement, (b) speaker position and the wall of climatic room without a sample, (c) speaker position and sample position on the wall of climatic room during sound-damping test.

RESULTS AND DISCUSSIONS

Effect of Water Hyacinth Content and Alkali Treatment on Flexural Properties

The flexural modulus and strength of the UP/WH composites obtained from the Box-Behnken experimental matrix are summarized in Table 3. To indicate experimental variability and repeatability, the overall mean ± standard deviation across all composite formulations as well as at the replicated center point are reported. The relatively low standard deviations observed at the center point confirm good experimental consistency under identical processing conditions. Overall, incorporation of water hyacinth fibers resulted in a reduction of flexural properties compared to neat UP, with the extent of degradation strongly dependent on WH content and alkali treatment conditions. Composite samples exhibited flexural modulus values ranging from 485 to 5814 MPa and flexural strength values between 3.2 and 44.6 MPa, indicating a wide property window governed by formulation parameters.

Increasing WH content caused a pronounced decrease in both flexural modulus and strength. At 60 wt% WH, flexural modulus and strength dropped by up to 88% and 96%, respectively, relative to the control sample. This trend is consistent with previous studies on natural fiber-reinforced polyester composites and is primarily attributed to inefficient stress transfer at high filler loading. As WH content increases, the available resin becomes insufficient to fully wet and encapsulate the filler, leading to poor interfacial adhesion and increased defect density within the composite structure [9], [19], [20]. In contrast, composites containing 30 wt% WH exhibited flexural modulus values ranging from 3420 to 5814 MPa, depending on the alkali treatment condition. Notably, the highest modulus was obtained under the milder treatment conditions (7.5% NaOH), indicating that moderate WH incorporation can enhance flexural stiffness under

suitable processing conditions. However, the variation among the 30 wt% WH formulations also demonstrates that the mechanical response is strongly dependent on the NaOH concentration and treatment duration.

Table 3. Flexural modulus and strength of UP/WH composites.

Run	WH [%]	Fibre Treatment		Modulus [MPa]	Change [%]	Strength [MPa]	Change [%]
		NaOH [%]	Duration [hr]				
Control	0	0	0	4190	0	78.5	0%
1	45	10.0	8	1790	-57%	23.6	-70%
2	30	10.0	5	3420	-18%	43.1	-45%
3	45	7.5	5	3164	-24%	30.7	-61%
4	45	7.5	5	3176	-24%	30.4	-61%
5	45	7.5	5	2433	-42%	26.4	-66%
6	30	5.0	5	3921	-6%	41.3	-47%
7	60	10.0	5	485	-88%	3.2	-96%
8	45	10.0	2	2363	-44%	26.5	-66%
9	45	5.0	8	3038	-27%	29.4	-63%
10	60	7.5	8	855	-80%	7.9	-90%
11	45	5.0	2	3041	-27%	33.5	-57%
12	60	5.0	5	650	-84%	6.8	-91%
13	60	7.5	2	1187	-72%	10.7	-86%
14	30	7.5	2	5256	+25%	44.3	-44%
15	30	7.5	8	5814	+39%	44.6	-43%
Average of all composite samples				2706±1575		26.8±14	
Average of mid-points				2924±426		29.2±2.4	

The relatively high flexural modulus observed in some 30 wt% WH composites (Run 14 and 15) compared with neat UP (4190 MPa) indicates that WH can provide an effective stiffness contribution when the fiber-matrix interface is developed. The increase in stiffness under favorable treatment conditions can be attributed to the rigid WH particles acting as load-bearing reinforcement and to improved fiber-matrix contact following alkali treatment, which facilitates stress transfer from the UP matrix to the WH phase. Conversely, the lower modulus obtained under other treatment conditions suggests that insufficient or excessive alkali treatment may limit reinforcement efficiency through less effective interfacial bonding or deterioration of the fiber structure.

Statistical analysis, shown in Table 4 and 5, suggested that WH content was the most influential factor affecting both flexural modulus and strength ($p < 0.001$). For flexural modulus, the quadratic effect of NaOH concentration was statistically significant ($p = 0.012$), whereas for flexural strength, the quadratic effect of WH content was significant ($p = 0.045$). The linear effects of NaOH concentration and treatment duration were not statistically significant for either response within the investigated range.

Statistical Modelling and Response Surface Analysis

Second-order polynomial models, equation 2 and 3, were developed to describe the relationship between processing variables and flexural responses. Second-order polynomial models, given in Equations (2) and (3), were developed to describe the relationship between the processing variables and the flexural responses. Both models exhibited high coefficients of determination ($R^2 > 0.90$). The analysis of variance identified WH content as the dominant factor for both responses, while significant quadratic effects were observed for NaOH concentration in the flexural modulus model ($p = 0.012$) and WH content in the flexural strength model ($p = 0.045$). None of the two-factor interaction terms was statistically significant ($p > 0.05$). The lack-of-fit tests were also not significant for the flexural modulus ($p = 0.513$) and flexural strength ($p = 0.498$) models, indicating no significant lack-of-fit relative to the pure experimental error.

$$Modulus = 2898 - 1904 * \%WH - 324 * \%NaOH - 44 * Time - 759 * \%NaOH * \%NaOH + 400 * Time * Time \quad (2)$$

$$Strength = 29.1 - 18.1 * \%WH - 1.8 * \%NaOH - 1.2 * Time - 3.5 * \%WH * \%WH - 2.1 * \%NaOH * \%NaOH + 1.2 * Time * Time - 1.4 * \%WH * \%NaOH - 0.8 * \%WH * Time + 0.3 * \%NaOH * Time \quad (3)$$

The contour plots in Figure 4 (a-f) illustrate the combined effects of WH content and NaOH concentration at different treatment durations. The response surfaces indicate that WH content exerted the strongest influence on the flexural responses, while the effects of the alkali-treatment variables were comparatively smaller within the investigated design space. For flexural modulus, the response surface exhibited a nonlinear tendency with respect to NaOH concentration, consistent with the statistically significant quadratic effect of NaOH concentration (p = 0.012). This suggests that the influence of alkali treatment on stiffness was not strictly linear within the investigated range. In contrast, the quadratic effect of NaOH concentration was not statistically significant for flexural strength (p = 0.168). The significant quadratic effect of WH content on flexural strength (p = 0.045) indicates a nonlinear response of strength to filler loading, consistent with the pronounced deterioration observed at high WH contents. At lower concentrations, alkali treatment may be insufficient to remove surface impurities such as lignin and waxes, limiting fiber-matrix adhesion. Conversely, excessive NaOH concentrations can degrade cellulose chains, leading to fiber embrittlement and reduced reinforcement efficiency.

Table 4. Analysis of variance of the flexural modulus.

Source	Modulus				
	DF	Adj SS	Adj MS	F-Value	p-value
Model	5	32775379	6555076	30.24	0.000
Linear	3	29864465	9954822	45.93	0.000
%WH	1	29009345	29009345	133.84	0.000
%NaOH	1	839808	839808	3.87	0.081
Time	1	15312	15312	0.07	0.796
Square	2	2910914	1455457	6.72	0.016
%WH*%WH					
%NaOH*%NaOH	1	2141899	2141899	9.88	0.012
Time*Time	1	593143	593143	2.74	0.132
2-way Interaction					
%WH*%NaOH					
%WH*%Time					
%NaOH*Time					
Error	9	1950691	216743		
Lack-of-Fit	7	1588507	226930	1.25	0.513
Pure Error	2	362185	181092		
Total	14	34726070			
Model Summary					
S			465.557		
R^2			94%		
R^2 (adjusted)			91%		
R^2 (predicted)			84%		

Table 5. Analysis of variance of the flexural strength.

Source	Modulus				
	DF	Adj SS	Adj MS	F-Value	p-value
Model	9	2731.43	303.49	48.51	0.000
Linear	3	2655.19	885.06	141.46	0.000
%WH	1	2617.26	2617.26	418.30	0.000
%NaOH	1	26.65	26.65	4.26	0.094
Time	1	11.28	11.28	1.80	0.237
Square	3	66.19	22.06	3.53	0.104
%WH*%WH	1	44.48	44.48	7.11	0.045
%NaOH*%NaOH	1	16.22	16.22	2.59	0.168
Time*Time	1	5.13	5.13	0.82	0.407
2-way Interaction	3	10.05	3.35	0.54	0.330
%WH*%NaOH	1	7.29	7.29	1.17	0.563
%WH*%Time	1	2.40	2.40	0.38	0.820
%NaOH*Time	1	0.36	0.36	0.06	0.000
Error	5	31.28	6.26		
Lack-of-Fit	3	19.76	6.59	1.14	0.498
Pure Error	2	11.53	5.76		
Total	14	2762.71			

Model Summary	
S	2.50137
R^2	99%
R^2 (adjusted)	97%
R^2 (predicted)	88%

Response surface optimization, as shown in Figure 4 (g-h), predicted that a formulation containing 30 wt% WH, 5 wt% NaOH, and a 2 h treatment duration would provide a flexural modulus of approximately 4810 MPa and a flexural strength of approximately 44.5 MPa, exceeding the minimum requirements specified by the Indonesian standard for wood composites (SNI 8154:2015). These values represent model predictions rather than experimentally measured confirmation results. Because no additional confirmation experiment was conducted at the predicted optimum, this formulation should be regarded as a model-derived optimum rather than an experimentally validated optimum. The optimization therefore provides a formulation target for future experimental validation rather than a confirmed optimum.

Morphological Analysis and Mechanical Correlation

Scanning electron microscopy was employed to elucidate the microstructural origins of the observed mechanical behaviour. SEM images of composites containing 30 wt% WH, Figure 5 (a), displayed relatively uniform filler dispersion and effective encapsulation by the UP matrix, suggesting adequate interfacial adhesion and efficient stress transfer. These morphological features correlate directly with the higher flexural modulus and strength measured for these samples.

At 45 wt% WH, Figure 5 (b), the microstructure revealed increased filler agglomeration and the presence of detached particles, indicating partial debonding at the filler-matrix interface. This microstructural degradation was more pronounced at 60 wt% WH, Figure 5 (c), where extensive particle segregation, voids, and unembedded fibres were observed. Such features act as stress concentrators and inhibit load transfer, explaining the severe loss of flexural performance at high WH loading. These observations support classical composite stress transfer theory, wherein reinforcement effectiveness is strongly governed by interfacial adhesion and filler dispersion. Once the critical filler volume fraction is exceeded, further addition of WH fibres contributes more defects than reinforcement, resulting in diminished mechanical performance.

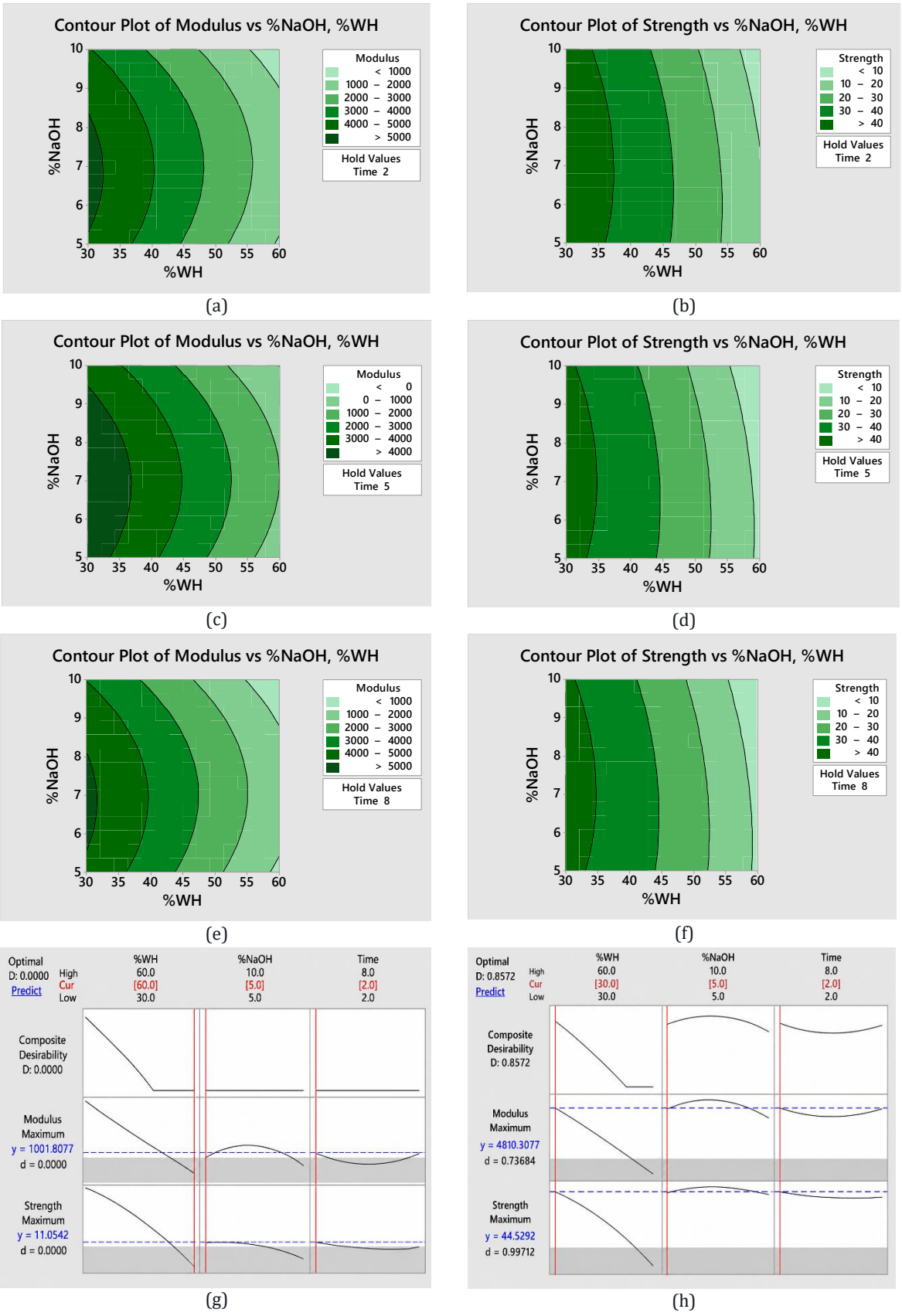


Figure 4. Contour and response optimizer plots of the flexural modulus and strength of the UP/WH composites: a - b) 2 hours, c - d) 5 hours, e - f) 8 hours, g) optimization plot at maximum %WH, h) optimization plot at minimum alkali treatment conditions

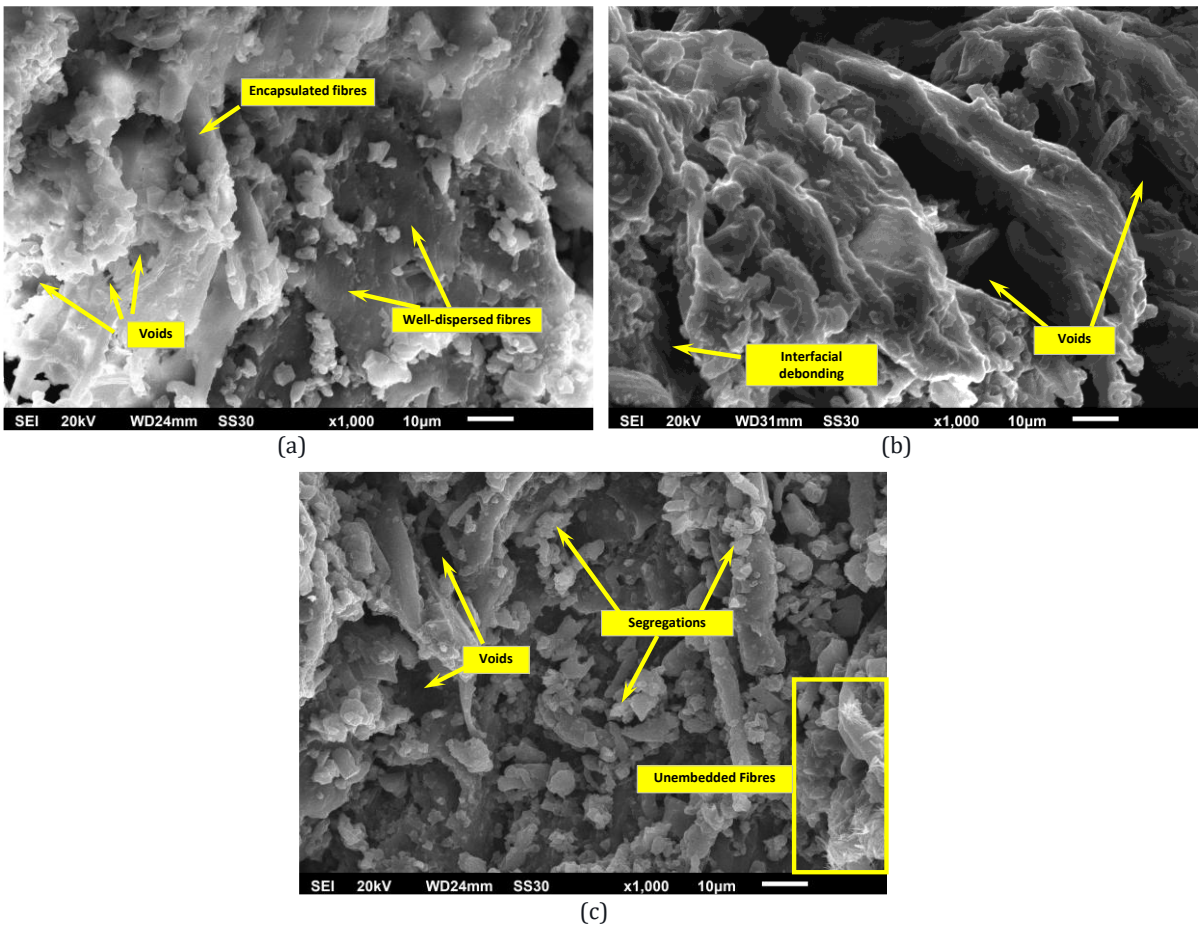


Figure 5. SEM images of selected UP/WH composites at various WH: (a) 30%, (b) 45% and (c) 60%

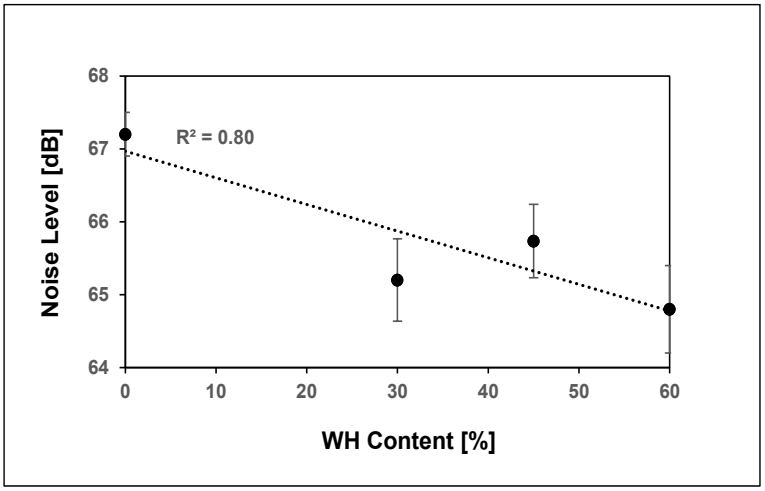


Figure 6. Sound damping performance of selected UP/WH composites at various WH: (a) 30%, (b) 45% and (c) 60%

Sound-Damping Performance and Structure-Property Relationship

The acoustic measurements at 100 Hz were conducted as a preliminary screening to compare the relative sound-damping response of the different UP/WH formulations under a controlled low-frequency excitation. This single-frequency measurement should not be interpreted as a comprehensive characterization of the acoustic performance of the composites.

The sound-damping performance of selected UP/WH composites is presented in Figure 6. The present acoustic evaluation was intended as a comparative screening method rather than a full characterization of sound absorption coefficients as defined in standardized acoustic testing protocols. Nevertheless, the observed noise reduction trend is consistent with established

absorption mechanisms in porous natural-fiber-based materials. The results show a progressive reduction in transmitted noise level with increasing WH content. The control sample exhibited an average sound level of 67.2 ± 0.3 dB, while composites containing 60 wt% WH reduced the sound level to 64.8 ± 0.6 dB, corresponding to an approximate 4% reduction.

The enhanced sound attenuation at higher WH contents can be attributed to the porous and hollow structure of WH fibers, which promotes internal sound energy dissipation through viscous and thermal losses. As sound waves penetrate the composite, energy is partially absorbed within the interconnected pores and irregular internal surfaces of the WH filler [6]. However, the improvement in acoustic performance occurs at the expense of mechanical integrity. The same porosity and reduced matrix continuity that favour sound attenuation also weaken the load-bearing capacity of the composite. This trade-off highlights a fundamental challenge in the design of natural fiber-based sound-damping materials and reinforces the need for application-specific optimization rather than maximizing a single performance metric.

The use of a single 100 Hz excitation also represents a limitation of the present study. Actual pump noise in industrial facilities is generally composed of multiple frequency components rather than a single discrete tone. Therefore, the observed reduction in sound level at 100 Hz provides comparative evidence of low-frequency attenuation but cannot be directly extrapolated to broadband pump-noise reduction. Future studies should characterize the acoustic response over a wider frequency range using standardized acoustic measurements to establish frequency-dependent sound absorption or transmission-loss behavior.

Balancing Mechanical Integrity and Acoustic Functionality

By integrating mechanical testing, acoustic screening, and statistical modeling, this study identified a model-predicted formulation window for UP/WH composites. Response surface modeling predicted that a formulation containing approximately 30 wt% WH, treated with 5 wt% NaOH for 2 h, would provide a flexural modulus of approximately 4810 MPa and a flexural strength of 44 MPa, while retaining measurable sound-damping capability. The predicted mechanical performance meets the requirements of the Indonesian standard for non-structural wood-based panels, although experimental confirmation of the predicted formulation is required.

In contrast, excessive WH incorporation, although beneficial for sound attenuation, leads to unacceptable mechanical degradation due to poor matrix wetting and interfacial failure. These findings emphasize that WH-based composites should be designed based on functional requirements rather than solely on maximizing filler content or acoustic performance.

From a sustainability perspective, utilizing water hyacinth as a composite filler offers a potential route for valorizing invasive aquatic biomass while reducing dependence on mineral fillers for non-structural acoustic panels. The model-predicted formulation identified in this study uses a relatively low alkali concentration (5 wt% NaOH) and a short treatment duration (2 h). Under an equivalent solution-to-fiber ratio, reducing the NaOH concentration from 7.5 to 5 wt% would correspond to a 33.3% reduction in the nominal NaOH requirement. However, the environmental implications of alkali consumption, wastewater generation, and energy demand were not quantitatively evaluated in this work. Therefore, a comprehensive life-cycle assessment is recommended in future studies to verify the environmental benefits and scalability of the proposed composite manufacturing process.

CONCLUSIONS

Unsaturated polyester (UP)/water hyacinth (WH) composites were successfully developed and evaluated as sound-damping panels for non-structural applications in water-exposed environments. The results demonstrate that WH incorporation significantly influences both mechanical and acoustic performance, with WH content identified as the dominant factor governing composite behavior. Increasing WH loading enhanced sound attenuation due to the porous structure of WH; however, excessive filler incorporation caused severe degradation in flexural modulus and strength as a result of poor matrix wetting, reduced interfacial adhesion, and inefficient stress transfer.

Statistical analysis using a Box-Behnken design identified WH content as the dominant factor affecting both flexural modulus and strength. A significant quadratic effect of NaOH concentration was observed for flexural modulus, whereas a significant quadratic effect of WH content was

observed for flexural strength. Response surface optimization predicted a formulation of 30 wt% WH, 5 wt% NaOH, and 2 h treatment as the model-derived optimum. Under these conditions, composites containing 30 wt% WH achieved a flexural modulus of approximately 4810 MPa and a flexural strength of about 44 MPa, satisfying the minimum requirements of the Indonesian standard for wood composites. Higher WH contents (≥ 45 wt%) provided improved sound-damping capability but resulted in mechanically unsuitable materials for load-bearing or semi-structural use.

Overall, this study highlights the inherent trade-off between acoustic functionality and mechanical integrity in WH-based composites and underscores the necessity of systematic formulation optimization rather than maximizing filler content. The optimized UP/WH composites presented herein offer a viable approach for converting invasive WH biomass into functional sound-damping panels suitable for pump houses and coastal food-processing facilities, where moisture resistance, durability, and controlled noise reduction are required.

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DECLARATION OF CONFLICTING INTERESTS

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AUTHOR CONTRIBUTIONS

David Natanael Vicarneltor: conceptualisation, methodology, investigation, writing - original draft. Onny Ujianto: supervision, validation, review and editing. Dwi Novriadi: testing. Opa Fajar Muslim: testing. Muhammad Luqman Saiful Fikri: review and editing

USE OF GENERATIVE AI

No generative AI tools were used in the preparation of this manuscript.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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