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NATURAL ANTIFUNGAL AGENTS FROM *PANGIUM EDULE* AND *PINUS MERKUSII* FOR THE WOOD-DECAYING FUNGUS *SCHIZOPHYLLUM COMMUNE*

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Abstract: *The demand for wood from community and plantation forests has increased as an alternative to natural forests. However, these fast-growing woods are often vulnerable to biodeterioration by wood-decaying fungi. Enhancing their durability through eco-friendly preservation methods is therefore essential. This study evaluated the antifungal efficacy of extracts from the leaves and seed shells of Pangium edule and from the leaves and fruits of Pinus merkusii against the wood-decaying fungus Schizophyllum commune at concentrations below 25 ppm. The extracts were tested at four concentration levels (5, 10, 15, and 20 ppm; w/v, mg extract per litre of agar) using the poisoned food technique on malt extract agar (MEA) medium. All extracts exhibited strong inhibitory activity, with the seed shell extract of P. edule achieving 100% inhibition (Antifungal Activity Index, AFA = 100%) across all concentrations. The fruit extract of P. merkusii produced AFA values ranging from 96% to 98%, while the leaf extracts from both species demonstrated slightly lower but still "very strong" activity (AFA > 80%). Notably, none of the treatments allowed complete fungal colony development compared to the control group. These findings suggest that both P. edule and P. merkusii extracts exhibit strong antifungal potential against S. commune in vitro. Further studies involving standardised wood-block decay tests are necessary to confirm their applicability as natural wood preservatives in practical use.*

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1. Introduction

Wood is a renewable, biodegradable, and versatile material that has been widely used for construction, furniture, packaging, and many other applications. However, it is inherently vulnerable to biological deterioration, particularly by fungi, insects, and bacteria. Among these, fungal decay poses one of the most serious challenges due to its ability to compromise the structural and aesthetic qualities of wood in a relatively short time. This problem is more pronounced in tropical regions where warm and humid conditions promote fungal growth. In such environments, wood-decaying fungi such as *Schizophyllum commune*, *Trametes versicolor*, and *Gloeophyllum trabeum* are commonly found degrading timber products during storage, transportation or in service. The resulting damage leads to substantial economic losses, both at the local and industrial scale. Some estimates suggest that losses due to fungal degradation of wood in tropical countries could account for a significant portion of the timber harvested before it reaches its intended use [10].

To address this issue, synthetic chemical preservatives such as chromated copper arsenate (*CCA*), pentachlorophenol (*PCP*), and copper-based formulations have been widely used for decades. These preservatives have proven effective in prolonging wood service life and protecting against fungal attack. However, increasing environmental concerns and regulatory restrictions, particularly in Europe and North America, have led to a gradual phase-out of many of these synthetic compounds due to their toxicity, persistence, and potential for bioaccumulation. This has encouraged researchers and industries alike to explore greener, safer, and sustainable alternatives to conventional wood preservatives.

A recent comprehensive review highlighted advances in bio-based wood protection systems, including plant-derived bioactive compounds, which are known to possess antimicrobial, insecticidal and antifungal properties with minimal environmental risks [6].

Natural products, including essential oils, tannins, alkaloids, and polyphenols extracted from various plants, have demonstrated potential as eco-friendly biocides [5]. These compounds offer advantages such as low toxicity and biodegradability, and can often be sourced from agroforestry residues or non-timber forest products. Research has highlighted the antifungal activity of plant extracts against various fungi, with studies exploring extracts from plants like *Michelia champaca*, *Pangium edule*, and *Tamarindus indica* [3], as well as *Sesbania grandiflora* [13]. Furthermore, the effectiveness of essential oils like *Cymbopogon nardus* in combination with other antifungal agents has also been reported [14]. These findings support the feasibility of using botanicals as part of integrated wood protection systems. However, the performance of plant extracts is known to vary depending on plant species, part used, extraction method, solvent polarity, and application concentration. Therefore, the systematic

evaluation of indigenous plant species remains a crucial step toward identifying locally available, effective bio-preservatives.

In this context, *Pangium edule* and *Pinus merkusii* are two tropical species native to Southeast Asia, including Indonesia, that contain a diverse array of secondary metabolites with documented antimicrobial activity. *Pangium edule*, traditionally known as "kepayang," is known to contain saponins, tannins, and cyanogenic glycosides, whereas *Pinus merkusii*, the only pine species native to the tropics, is rich in terpenoids and flavonoids. Previous research by our group demonstrated that extracts from *P. edule* and *P. merkusii* can effectively inhibit *Schizophyllum commune* at concentrations of 25-100 ppm [27]. However, there remains a need to investigate their antifungal performance at lower, sub-threshold concentrations to improve dosage efficiency and applicability for commercial-scale use. For example, nanoencapsulation of *Zataria multiflora* essential oil has been shown to enhance its antifungal activity against *Botrytis cinerea*, suggesting a potential strategy for reducing the required concentration of biocides [16]. This is particularly relevant given the industrial demand for reduced biocide loading to meet eco-labelling criteria and cost-effective treatment processes.

Comparison of the present study and Taskirawati et al. [27] Table 1

Parameter	Taskirawati et al. [27]	Present study (2025)
Plant parts used	Leaves and seed shells of *Pangium edule*	Leaves and seed shells (*P. edule*), fruits and leaves (*P. merkusii*)
Extract concentrations	25, 50, 75, 100 ppm	5, 10, 15, 20 ppm
Target fungus	*Schizophyllum commune*	*Schizophyllum commune*
Test method	Agar-based poisoned food technique	Agar-based poisoned food technique
Evaluation parameter	Fungal colony diameter	Antifungal Activity Index (*AFA*)

Therefore, the present study aims to evaluate the antifungal efficacy of *P. edule* and *P. merkusii* extracts at concentrations below 25 ppm, specifically at 5, 10, 15, and 20 ppm. This study also expands the range of plant parts used, including fruits and leaves of *P. merkusii* and seed shells of *P. edule*, to investigate potential differences in activity. To clearly differentiate the present work from our previous study [27] and to address potential redundancy, a summary comparison is presented in Table 1. The focus on lower dosage screening aligns with current trends in sustainable forestry product development and aims to support the advancement of locally sourced, plant-based wood protection solutions.

2. Material and Methods

2.1. Plant Material Preparation and Extraction

Leaves and seed shells of *Pangium edule* were collected from Maros Regency (04°59′37″S, 119°40′09″E), and leaves and fruits of *Pinus merkusii* were collected from Malino, Gowa Regency (05°15′03″S,

119°53'42"E), South Sulawesi, Indonesia. The plant materials were taxonomically identified based on morphological characteristics using standard references, and representative samples were retained for potential future voucher deposition at the Herbarium of the Faculty of Forestry, Universitas Hasanuddin.

The collected materials were air-dried at room temperature and ground into fine powder using a mechanical grinder. Each 100 g of powdered sample was macerated in 300 mL of analytical-grade methanol (1:3 w/v) for 72 hours at ambient temperature with occasional shaking, following the method of Ibrahim and Sitorus [11]. The mixture was filtered using Whatman no. 1 filter paper, and the process was repeated until the filtrate became clear. The combined filtrates were concentrated using a rotary evaporator under reduced pressure at 45°C. The resulting crude extract was further air-dried in a fume hood for 24 hours until a constant weight was obtained and no solvent odour remained. The dried extracts were stored at 4°C in sealed containers until further use.

2.2. Preparation of Inoculation Media

Malt Extract Agar (*MEA*) was prepared by dissolving 48 g of malt extract powder in 1 L of distilled water. The mixture was homogenised, sterilised in an autoclave at 120 ± 2°C (1.5 atm) for 15 minutes, and poured into sterile Petri dishes under laminar airflow. The wood-decaying fungus *Schizophyllum commune* was previously isolated from decayed wood and maintained on *MEA* at 28°C for use in antifungal assays.

2.3. Antifungal Activity Assay

Stock solutions of each plant extract were prepared at 1,000 ppm by dissolving the dried extract in methanol. Working concentrations of 5, 10, 15, and 20 ppm were obtained by serial dilution in sterile distilled water. For each treatment, 2 mL of the working solution was mixed with 20 mL of molten *MEA* (approximately 40°C), poured into sterile Petri dishes, and left under laminar airflow for 2 hours to ensure the complete evaporation of residual methanol. The stated ppm concentrations refer to the final concentration of extract in the agar medium (w/v), calculated based on the total volume after addition to molten MEA.

A single control group was used, consisting of MEA without any extract or added solvent. Once solidified, a 5 mm-diameter mycelial plug of actively growing *S. commune* was placed at the centre of each plate. All plates were incubated at 28°C for 12 days. Colony diameters were measured on Day 12 using a digital calliper. Each treatment and control were performed in five replicates.

2.4. Antifungal Activity Index (*AFA*)

Antifungal activity was quantified using the Antifungal Activity Index (*AFA*), calculated with Equation (1) – [17].

$$AFA = \frac{D_K - D_P}{D_K} \cdot 100 \quad [\%] \qquad (1)$$

where:

AFS is the antifungal activity index [%];

D_K – the average colony diameter of the control [cm];

D_P – the that of the treatment [cm].

AFA values were interpreted based on categorical inhibition classes, as summarised in Table 2.

2.5. Data Analysis

The experiment was arranged in a two-factor completely randomised design with five replicates. Factor 1 was plant extract type (*P. edule, P. merkusii*) and factor 2 was extract concentration (5, 10, 15, 20 ppm). Data were analysed using two-way analysis of variance (ANOVA), followed by Tukey's HSD test to determine significant differences between treatments at $p \leq 0.05$. All data are presented as mean ± standard deviation (*SD*). Statistical analyses were conducted using SPSS version 26.

Classification of antifungal activity based on AFA values Table 2

Antifungal Activity Index (*AFA* – [%])	Category
>75	Very Strong
50–75	Strong
25–50	Moderate
0–25	Weak
0	Inactive

3. Results

The antifungal activity of various plant extracts against *Schizophyllum commune* was evaluated by calculating the Antifungal Activity Index (*AFA*) based on colony diameter measurements taken on day 12 after inoculation. The experiment followed a two-way ANOVA design with two factors: extract type and concentration. All treatments yielded AFA values exceeding 75%, classifying them as having "very strong" antifungal effects according to the categorical scale. However, the statistical analysis revealed significant differences between extract types and concentrations ($p \leq 0.05$), as summarised in Table 3.

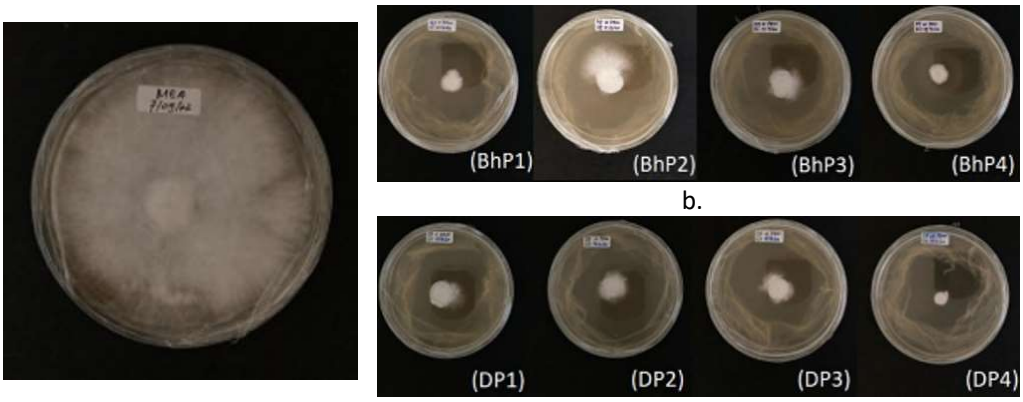
Antifungal Activity (% mean ± SD) of extracts against Schizophyllum commune at various concentrations Table 3

Extract	Concentration [ppm]			
	5	10	15	20
Seed shells of *Pangium edule*	100.00±0.00 (c)	100.00±0.00 (c)	100.00±0.00 (c)	100.00±0.00 (c)
Leaves of *Pangium edule*	95.96±1.89 (bc)	94.38±3.81 (bc)	97.75±1.59 (bc)	97.98±1.23 (bc)
Fruits of *Pinus merkusii*	95.51±0.00 (bc)	96.63±1.12 (bc)	97.75±3.08 (bc)	96.63±0.79 (bc)
Leaves of *Pinus merkusii*	79.55±10.09 (a)	85.39±3.18 (a)	92.81±1.01 (b)	97.53±2.30 (bc)

Note: The letters in parentheses indicate the results of Tukey's multiple comparison test at a 5% significance level. The values sharing the same letter are not significantly different. The values after the ± symbol represent standard deviations.

These differences were further clarified through grouping with Tukey's HSD test, allowing the identification of distinct efficacy profiles among the tested treatments.

The seed shell extract of *Pangium edule* consistently exhibited the highest antifungal performance, with AFA values of 100.00 ± 0.00% across all concentrations tested (5, 10, 15, and 20 ppm). These results placed it in the highest statistical group (Tukey's group c) and confirmed its complete inhibition of fungal colony development. Visual evidence of this total inhibition is shown in Figure 1b, where no observable fungal growth was present at any concentration level. This consistent performance across concentrations highlights the potential of the seed shell extract as a highly potent bioactive antifungal agent.



a. b. c.

Fig. 1. *Visual evidence of the total inhibition: a. Control; b. Pangium edule Reinw. seed shell extract [BhP1: 5 ppm; BhP2: 10 ppm; BhP3: 15 ppm; BhP4: 20 ppm]; c. Pangium edule leaf extract [DP1: 5 ppm; DP2: 10 ppm; DP3: 15 ppm; DP4: 20 ppm]*

The leaf extract of *P. edule* also demonstrated strong inhibitory activity, though slightly less consistent than the seed shell counterpart. The *AFA* values ranged from 95.96 ± 1.89% at 5 ppm to 97.98 ± 1.23% at 20 ppm, all falling under the "very strong" category and grouped statistically in category (*bc*) (Table 3). The pattern of fungal growth inhibition for this extract is illustrated in Figure 1c. These results suggest that while leaf extract is also highly effective, the bioactive compound concentration or availability may vary slightly depending on the plant part.

The fruit extract of *Pinus merkusii* showed comparable antifungal performance to the *P. edule* leaf extract. The *AFA* values ranged from 95.51 ± 0.00% at 5 ppm to 97.75 ± 3.08% at 15 ppm, and all were categorised within group (*bc*) in the Tukey analysis. The efficacy pattern is observable in Figure 2b, where fungal growth was consistently suppressed, but not completely eliminated. These results imply that *P. merkusii* fruit extract has a high potential as a natural inhibitor, though

slightly less uniform than the *P. edule* seed shell extract.

In contrast, the leaf extract of *P. merkusii* demonstrated the lowest antifungal performance at the lowest concentration tested. At 5 ppm, the *AFA* was 79.55 ± 10.09%, which, although still classified as "very strong," was statistically lower than all other treatments and grouped under Tukey's category (a). However, this extract showed a notable concentration-dependent effect, with the *AFA* increasing to 97.53 ± 2.30% at 20 ppm, as seen in Figure 2c and Table 3. These findings indicate that while *P. merkusii* leaf extract is less potent at low doses, its effectiveness improves substantially with increased concentration, highlighting a dose–response relationship.

Overall, both *Pangium edule* and *Pinus merkusii* extracts demonstrated strong antifungal properties against *S. commune*. The effectiveness varied by plant part and concentration, with the seed shell of *P. edule* emerging as the most consistent and potent treatment. The data in Table 3 and the visual confirmation in Figures 1 and 2 clearly support these conclusions, confirming that both the chemical composition of each plant part and the applied dose are critical factors in determining antifungal efficacy.

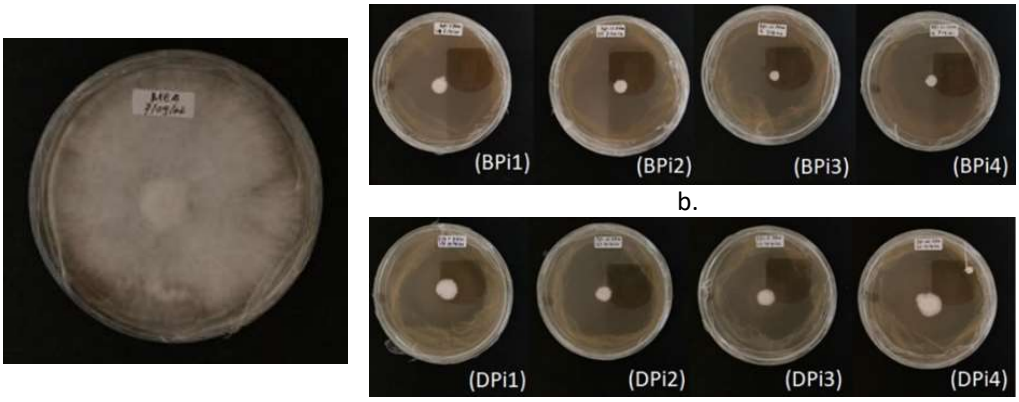


Fig. 2. *The eficacy patern: a. Control; b. Pinus merkusii fruit extract [BPi1: 5 ppm; BPi2: 10 ppm; BPi3: 15 ppm; BPi4: 20 ppm]; c. Pinus merkusii leaf extract [DPi1: 5 ppm; DPi2: 10 ppm; DPi3: 15 ppm; DPi4: 20 ppm]*

4. Discussion

The findings of this study demonstrate that all tested extracts from *Pangium edule* and *Pinus merkusii* exhibited strong antifungal activity against *Schizophyllum commune*, with *AFA* values exceeding 75% across all treatments. These results confirm that both plant species contain bioactive compounds with significant inhibitory effects on the growth of wood-decaying fungi and reinforce their potential as natural antifungal agents for sustainable wood protection applications.

Among all treatments, the seed shell extract of *P. edule* emerged as the most effective, consistently achieving complete growth inhibition (100% *AFA*) across all concentrations. This aligns with the findings of Taskirawati et al. [27], who also

reported complete inhibition of *Schizophyllum commune* by *P. edule* leaf and seed shell extracts at concentrations ranging from 25 to 100 ppm. The superior activity of the seed shell extract may be attributed to its high content of secondary metabolites such as tannins, saponins, and cyanogenic glycosides, which are known to disrupt fungal cell walls and inhibit enzymatic activity [22]. The antifungal action of such natural compounds aligns with research demonstrating that plant-derived chemicals, such as flavonoids and essential oils (including oleoresins and monoterpenes), exhibit broad-spectrum antifungal and antibacterial properties [8, 28]. Although the specific compounds responsible for antifungal activity were not characterised in this study, the discussion of flavonoids and terpenoids is based on previous phytochemical reports and should be considered as hypothetical mechanisms requiring further chemical profiling (e.g., *GC–MS* or *LC-MS/MS*). The complete absence of growth in this treatment suggests fungicidal, rather than merely fungistatic, action.

From a wood protection perspective, the observed inhibitory effects support the potential application of botanical extracts as natural preservatives. This approach aligns with the current drive toward developing environmentally benign wood protection systems that combine organic biocides with antioxidants and metal chelators to reduce ecological impact [24]. The concept of using plant-based substances for wood preservation has been extensively reviewed, highlighting their efficacy, availability, and potential integration into green chemistry frameworks [25]. In addition, essential oils extracted from various plant sources have demonstrated strong fungicidal and termiticidal activity, further validating their utility in wood product protection [12].

The leaf extract of *P. edule*, while also classified as "very strong" in terms of *AFA*, showed slightly lower and more variable inhibition compared to the seed shell. This discrepancy could be explained by differences in phytochemical composition between plant parts. Bena et al. [4] similarly observed high antifungal activity from *P. edule* leaves against *Botryodiplodia theobromae*, with efficacy increasing with concentration. The presence of flavonoids, terpenoids, and phenolic compounds in the leaves likely contributes to their antifungal effects, albeit to a lesser extent than the seed shell.

The fruit extract of *P. merkusii* demonstrated comparable efficacy to *P. edule* leaf extract, indicating its potential as an antifungal agent. Although not achieving complete inhibition, the *AFA* values remained above 95% across all concentrations, and no significant differences were found between this extract and *P. edule* leaf or *P. merkusii* fruit extracts. These results are consistent with findings by Arista et al. [2], who reported strong antifungal activity from *P. merkusii* extracts against *Auricularia auricula*-judae. The high terpene and phenolic content of *P. merkusii* fruit may contribute to membrane disruption and oxidative damage in fungal cells.

In contrast, the leaf extract of *P. merkusii* showed the lowest inhibition at 5 ppm (79.55% *AFA*), though still within the "very strong" category. The high standard deviation in this treatment suggests less consistency in performance, possibly due to lower concentrations of active compounds or variability in their extraction. However, as the concentration increased, the *AFA* values improved

substantially, reaching nearly 98% at 20 ppm. This clear dose-dependent effect underscores the importance of optimising concentration to achieve maximal efficacy, particularly for extracts with moderate inherent activity.

The results obtained in this study offer compelling evidence regarding the antifungal potential of *P. edule* and *P. merkusii* extracts against *S. commune*. Among the tested samples, the seed shell extract of *P. edule* consistently demonstrated complete inhibition of fungal growth across all tested concentrations (5 to 20 ppm), suggesting the presence of highly potent bioactive constituents in this specific plant tissue. This activity level, especially at low concentrations, is uncommon among plant-derived antifungal agents. Compared to the extracts of *P. merkusii*, which also showed inhibitory effects but with slightly lower consistency, *P. edule* seed shell extract exhibited superior potency and uniformity in response. The differential response between the leaf and fruit extracts of *P. merkusii* indicates the varying phytochemical composition among different plant organs, which may influence antifungal effectiveness.

Furthermore, the concentration-dependent inhibition observed particularly in *P. merkusii* leaf extract aligns with previous findings that higher levels of certain phytochemicals are required to suppress fungal growth. The fact that complete inhibition was achieved at concentrations as low as 5 ppm for *P. edule* seed shell extract is particularly significant for practical applications in wood protection. It indicates that smaller amounts of natural product may suffice, reducing the need for bulk processing or high solvent use during extraction. Such low-dose efficacy enhances economic feasibility and minimises environmental residue risks. From a biochemical standpoint, the results suggest a threshold effect, whereby a minimum concentration of active compounds saturates the fungal response mechanism, resulting in complete inhibition. This opens the door for more targeted preservative strategies in application settings, especially in treating fast-growing, low-durability timber species.

A comparative analysis with related literature further supports the robustness of these findings. Taskirawati et al. [27] found that *P. edule* extracts at 25–100 ppm inhibited *S. commune* growth, although the study did not observe complete inhibition at the lowest concentrations tested. In contrast, this study achieved complete inhibition at concentrations below 25 ppm, suggesting either differences in extract purity or the concentration of specific active compounds. Arista et al. [2] similarly observed strong antifungal activity of *P. merkusii* extracts against *Auricularia auricula*-judae, a fungus taxonomically related to *S. commune*. In both prior studies, the effectiveness of the extracts improved with increased concentrations, consistent with the current findings for *P. merkusii*.

Additionally, Listyorini et al. [15] reported the antifungal activity and major bioactive compounds of water extract of *Pangium edule* seed against *Aspergillus flavus*, further confirming its broad-spectrum antifungal potential. It is noteworthy that traditional plant-based antifungal agents such as dammar resin, citrus peel, and sindur wood extract required concentrations of 50,000 to 100,000 ppm to achieve comparable inhibition levels [18, 20, 26]. The marked

difference in effective concentration highlights the active compounds' superior potency and possibly greater extractability in *P. edule* and *P. merkusii*. Phenolic and flavonoid compounds found in tropical plants show potential as natural antifungal agents. The high content of phenolic and flavonoid compounds may contribute to their ability to inhibit mould growth, thus their potential use in wood protection [19]. Therefore, these findings position *P. edule* and *P. merkusii* as highly efficient antifungal agents among tropical plant resources.

The antifungal efficacy observed can be attributed to various phytochemicals, particularly secondary metabolites known for their antimicrobial properties. Recent phytochemical screening of *P. edule* confirmed the presence of alkaloids, tannins, saponins, flavonoids, and phenolics [7, 23], all of which have been associated with antifungal activity. These compounds disrupt fungal physiology by targeting cell wall integrity, ion transport channels, and mitochondrial activity. In the case of *P. merkusii*, terpenoids such as α-pinene and β-pinene, along with phenolic acids and flavonoids, have been identified as major constituents in its leaves and fruits [9, 21]. These lipophilic terpenoids have been shown to integrate into fungal membranes, causing leakage and cellular dysfunction. Moreover, phenolic compounds such as gallic acid and catechin can induce oxidative stress and interfere with the synthesis of ergosterol, a key component of fungal membranes. The combination of these bioactive components likely produces a synergistic effect, amplifying the overall antifungal action. The importance of synergy among plant compounds has been highlighted by several studies [3, 13, 14], which have shown that whole-plant extracts often exhibit greater biological effects than isolated compounds due to interactions among multiple active ingredients. Such interactions may explain why significant inhibition was observed in this study, even at low ppm concentrations. The phytochemical diversity within both species further supports their selection as viable candidates for antifungal applications, particularly in wood preservation, where long-term stability and broad-spectrum action are crucial.

From a wood protection perspective, plant-derived antifungal agents are gaining traction due to increasing restrictions on synthetic preservatives. Recent reviews have highlighted the growing demand for bio-based wood protective systems that align with environmental regulations and sustainability goals in the forestry sector [6]. The findings of this study are relevant in this context, as they highlight locally available tropical species with demonstrated efficacy at low dosages. Natural antifungal treatments can be an effective first-line defence in tropical regions where high humidity promotes rapid fungal growth. Moreover, *P. edule* and *P. merkusii* are abundant in various parts of Southeast Asia, making them practical and economically accessible. Their integration into community-based forestry initiatives could enhance local economies while reducing dependency on imported chemicals. The effective extract concentrations in this study also make them suitable for formulation into coatings, emulsions, or even solid wood treatment processes. Studies on nanoencapsulation of plant extracts show potential to improve stability, control release, and extend the shelf life of bioactive components [16]. Such

techniques could be explored further to improve the operational feasibility of *P. edule* and *P. merkusii* extracts in real-world applications.

Additionally, compatibility with pressure treatment systems or surface brushing techniques would determine their scalability. Further testing under outdoor weathering and microbial challenge conditions would be required to validate their protective efficacy over extended periods. Despite the promising in vitro results, the application of plant extracts in real-world wood protection must consider limitations such as leachability under rainfall, photodegradation from sunlight exposure, and possible ecotoxicity to non-target soil or aquatic organisms. Future research should address these parameters through leaching tests, UV-exposure simulations, and ecotoxicological screening. Although complete inhibition was achieved across all tested concentrations for *P. edule* seed shell extract, the use of only four concentration points limits the ability to estimate a precise minimum inhibitory concentration (*MIC*). Future studies should include lower concentration ranges (e.g., ≤ 1 ppm) and apply probit analysis or non-linear regression models to determine EC_{50} values and define the effective dose range.

Finally, it is essential to consider the broader scientific implications of these findings in the context of natural product chemistry and fungal biology. The consistent inhibition of *S. commune* – a model organism for wood-decay studies – indicates a strong bioactive interaction that warrants further mechanistic exploration. Several studies have shown that genetic manipulations in wood decay fungi, such as the expression of laccase gene homologs in *Gloeophyllum trabeum*, can affect lignin degradation ability [1]. This suggests that plant-derived phenolic compounds can modulate gene expression in fungi, potentially suppressing the expression of enzymes such as laccase and peroxidase, which are important for wood degradation. Applying transcriptomic or proteomic analysis could help elucidate whether similar downregulation occurs upon exposure to *P. edule* or *P. merkusii* extracts.

Additionally, given the complex metabolomic profile of tropical plants, future studies may uncover novel compounds or unique chemical synergies responsible for antifungal activity. Advanced profiling techniques such as *LC-MS/MS* and *NMR* spectroscopy could facilitate the identification of such active components. The high effectiveness observed also allows cross-disciplinary collaborations with materials science, microbiology, and chemical engineering. Understanding the interaction of plant extracts with fungal cell components at the molecular level may also contribute to the development of targeted bio-preservatives with minimal impact on non-target organisms. These findings thus create multiple research trajectories that can deepen our understanding of plant-fungal interactions, enhance natural product applications, and advance sustainable innovations in forestry.

5. Conclusions

This study demonstrated that methanolic extracts derived from the leaves and seed shells of *Pangium edule* and from the leaves and fruits of *Pinus merkusii* exhibit strong antifungal activity against *Schizophyllum commune* under in vitro conditions using an agar-based assay. All tested extracts significantly inhibited

fungal colony growth, with the seed shell extract of *P. edule* achieving complete inhibition across all tested concentrations (5-20 ppm). These findings indicate that both plant species, particularly *P. edule*, contain bioactive compounds with potential antifungal properties. While the results are promising, they are limited to controlled laboratory conditions. Further research, including wood-block decay tests and field simulations, is necessary to validate their efficacy and durability in practical wood protection applications.

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