

## BIOLOGICAL DEGRADATION OF BAMBOO PAPER BY TWO WHITE-ROT FUNGAL SPECIES

Novitri Hastuti<sup>1</sup>, Luciasih Agustini<sup>2</sup>, Erlina N. Aini<sup>1</sup>, Dian A. Indrawan<sup>1</sup>, Gustan Pari<sup>1</sup> and Heru Satrio Wibisono<sup>1</sup>

<sup>1</sup>Research Center for Biomass and Bioproducts, National Research and Innovation Agency, Kawasan Sains Teknologi Dr. (H.C.) Ir. H. Soekarno Jl. Raya Bogor Km. 46, 16911 Cibinong, Indonesia

<sup>2</sup>Research Center for Applied Microbiology, National Research and Innovation Agency, Kawasan Sains Teknologi Dr. (H.C.) Ir. H. Soekarno Jl. Raya Bogor Km. 46, 16911 Cibinong, Indonesia

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BIOLOGICAL DEGRADATION OF BAMBOO PAPER BY TWO WHITE-ROT FUNGAL SPECIES. Non-wood paper production, such as bamboo paper, is an alternative to meet the massive demand for paper consumption in the recent era. Bamboo paper, made from *Bambusa vulgaris* fibers and manufactured with the addition of activated nano-carbon, shows an improvement in paper quality. However, there is a potential worry with the incorporation of activated carbon since it may hinder the degradation process of paper. Concerning the substance's life cycle, degradation assisted by the fungal decomposer of this new product is crucial. This study investigated the effects of the white-rot fungi, viz. *Phlebiopsis* sp and *Pycnoporus* sp., on the degradation of bamboo paper with- or without- activated nano-carbon (BPAC and BPNAC). In vitro experiments that combined two variables (Fungal agents and Paper types) were carried out for 12 weeks. The results revealed that *Pycnoporus* sp. was more effective in decomposing both BPAC and BPNAC rather than *Phlebiopsis* sp. After being degraded by *Phlebiopsis* sp. and *Pycnoporus* sp. for 12 weeks, the remaining mass of BPAC was 64.14% and 48.96%, respectively, while the BPNAC was 69.89% and 38.25%, respectively. The ability of these fungal agents on composite-paper degradation was compared to other similar studies. Further investigation and possible applications were discussed.

Keywords: Bamboo, carbon, degradation, fungi, paper, white-rot

DEGRADASI BIOLOGIS KERTAS BAMBU OLEH DUA JENIS JAMUR PELAPUK PUTIH. Produksi kertas non-kayu, seperti kertas bambu, merupakan salah satu alternatif untuk memenuhi konsumsi kertas yang tinggi di era sekarang ini. Kertas bambu yang terbuat dari serat bambu ampel (*Bambusa vulgaris*) dan diproduksi dengan penambahan nano-karbon aktif, menunjukkan peningkatan kualitas kertas yang berpotensi sulit terdegradasi saat pengelolaan sampah. Mengingat pentingnya mempertimbangkan siklus-hidup suatu produk, penelitian degradasi kertas bambu komposit oleh jamur pengurai perlu dilakukan. Oleh karena itu, penelitian ini bertujuan untuk mengetahui pengaruh dua jenis jamur pelapuk putih, yaitu: *Phlebiopsis* sp dan *Pycnoporus* sp. pada degradasi kertas bambu yang diproduksi dengan- atau tanpa- penambahan nano-karbon aktif (BPAC dan BPNAC). Pengujian secara in vitro yang menggabungkan dua variabel, yaitu: jenis fungi dan tipe kertas dilakukan selama 12 minggu. Data menunjukkan bahwa *Pycnoporus* sp. lebih efektif dalam penguraian BPAC dan BPNAC daripada *Phlebiopsis* sp. Setelah didegradasi oleh *Phlebiopsis* sp. dan *Pycnoporus* sp. selama 12 minggu, berat kering BPAC yang tersisa sebesar 64,14% dan 48,96%; sedangkan BPNAC sebesar 69,89% dan 38,25%. Perbandingan kemampuan jamur pelapuk putih ini dalam mendegradasi kertas komposit dengan penelitian serupa, serta kebutuhan akan penelitian lebih lanjut dan potensi aplikasinya dibahas dalam naskah ini.

Kata kunci: Bambu, karbon, degradasi, jamur, kertas, pelapuk putih.

\*Corresponding author: novi043@brin.go.id

## I. INTRODUCTION

Paper is primarily composed of plant materials containing cellulose, hemicellulose, and lignin. Approximately 10,000 -D-glucopyranose units are interconnected by (1 → 4)-glucosidic bonds to form the cellulose molecules (Jablonsky & Sima, 2021). Coniferous and fast-growing plants are commonly used as resources of cellulose fibers for pulp and paper industries. However, recent studies reported that cellulose fibers from bamboo plants can be used as an alternative source for paper industries due to their growth rate and cellulose abundance. The daily growth of bamboo plants is 4 – 6 times higher, and its cellulose is 2 – 6 times greater than that of woody plants. Moreover, bamboo has a shorter harvesting time rather than woody plants. It can be harvested after 4 years of planting, while the woody plants need 8 – 20 years (Ainun et al., 2018; Herliyana, Noverita, & Sudirman, 2005).

The extensive use of paper in daily life has an effect on the environmental management of paper waste. The choice of plants as a source of cellulose fiber and the process of making paper will affect the lifespan and degradation process of the paper produced. A study on the kinetics of cellulose degradation of bamboo paper at room temperature expected that the paper could be preserved for more than a thousand years (Jin et al., 2022). Furthermore, many studies have reported that the addition of such nanomaterials, including nano-activated, may promote microstructure density, which will lead to the improvement of the mechanical properties of the material (Wu, Miao, Zhang, Gao, & Hui, 2020). Thus, the production of nano-activated carbon bamboo paper requires to be supplemented by its biodegradation study so that the scientific basis for developing waste management can be provided comprehensively.

Paper degradation is determined by the characteristics of the paper material and its interaction with environmental factors such as temperature, as well as the presence of microorganisms that initiate paper degradation (Refugio, Nieto-villena, Ángel, & Cruz-

mendoza, 2017). Cellulolytic microorganisms that produce cellulase enzymes are able to degrade cellulose, a significant component of paper. Cellulase has a system enzyme consisting of exo-1,4-β-glucanase, endo-1,4-β-glucanase, and -D-glucosidase. These three enzymes degrade cellulose and produce a sugar-reducing agent through a synergistic process (Purkan, Purnama, & Sumarsih, 2015). Exo-glucanase is active in crystalline cellulose and degrades disaccharide units from either the non-reducing or reducing end, whereas endoglucanase is active in the amorphous region of cellulose and can also hydrolyze substituted cellulose, including carboxymethyl cellulose (CMC) and hydroxyethyl cellulose (HEC), internally. D-glucosidase can additionally convert cellobiose and other soluble oligosaccharides into glucose (Mrudula & Murugammal, 2011).

Numerous microorganisms, i.e., bacteria, actinobacteria, yeasts, and filamentous fungi, produce cellulases. *Rhizumucor variabilis*, *Fusarium* sp., *F. solani*, *Aspergillus niger*, *Bacillus thuringiensis*, and *Sphingobacterium daejeonense* are some cellulolytic microbes that have been studied intensively (Agustini et al., 2012). Due to their capability in producing cellulases with high enzymatic activity, fungi of the genera *Clostridium*, *Cellulomonas*, *Thermomonospora*, *Trichoderma*, and *Aspergillus* are preferred to be applied as cellulolytic agents (Darwesh, El-maraghy, Abdel-rahman, & Zaghloul, 2020).

In addition, white rot fungi from the Basidiomycetes are also attractive to be utilized as cellulase-producing organisms due to their ability to degrade lignocellulosic substances (Baker, Charlton, & Hale, 2015; Bari et al., 2015). Apart from its ability to decompose cellulose and hemicellulose, this fungal group can also degrade lignin (Saito et al., 2018). Research related to the enzymatic activities of the white rot fungi mostly focused on the efficiency of lignin degradation, the types and activities of ligninolytic enzymes, and the characteristics of degradation products (Dong, Yang, Zhu, Wang, & Yuan, 2013). The aspect

of cellulolytic activity of the white rot fungi seems to have no significant progress. *Pycnoporus* sp. and *Phlebiopsis* sp. are some of the white rot fungi that have been studied for their cellulase activity, which demonstrated that the *Pycnoporus* isolate produces cellulase with higher activity than the *Phlebiopsis* isolate (Agustini et al., 2017).

The nano activated-carbons (ACs) added to the process of paper-making not only improve the quality of the paper but also release unique properties that can impede or even eliminate bacterial growth (de Jesús Barraza-García et al., 2022; Wu et al., 2020). From the perspective of its function as food packaging paper, these traits are beneficial. However, in terms of the product life span that will eventually be discarded, these positive characteristics potentially will make bamboo paper with activated nano-carbon (BPAC) difficult to degrade. Therefore, as an anticipation, it is necessary to search for biological agents other than bacteria to overcome this potential problem. White rot fungi can be an option. *Pycnoporus* sp. and *Phlebiopsis* sp., whose cellulolytic activities have been characterized (Agustini et al., 2017), can be tested for this purpose. Moreover, a study reported that the presence of carbonaceous products stimulated the proliferation of soil-resident fungi and enhanced the enzymatic activities (Taskin, Teresa, Altomare, & Loffredo, 2019).

Considering all the previous studies and the necessity to find biological agents for bamboo paper degradation, the experiments that tested the biodegradability of bamboo papers (with- or without- nano-activated carbon) were carried out. Therefore, this research aimed to examine whether the addition of nano-activated carbon to bamboo paper alters the biodegradability of the packaging paper and the enzyme activity of *Pycnoporus* sp. and *Phlebiopsis* sp. In this experiment, we used unbleached bamboo paper because it had lower production costs and was more eco-friendly compared to bleached paper. The low production cost and eco-friendly properties of paper for packaging are preferable nowadays.

## II. MATERIAL AND METHOD

### A. Materials

Papers made of Ampel bamboo fibers were used as the primary material. Activated carbon was created from sawdust by-products. Isolates of *Phlebiopsis* sp. FORDACC-02482 and *Pycnoporus* sp. FORDACC-03452 obtained from Indonesian Tropical Forest Culture Collections (INTROF-CC) was utilized in vitro fungi decay experiments. The fungal growth medium, Potato Dextrose Agar (PDA), was poured into petri dishes. All experiments employed deionized water. During the pulping process, sodium hydroxide was used without purification as a cooking solution.

### B. Methods

#### *Paper Preparation*

Our previous study (Indrawan, Hastuti, Efiyanti, & Pari, 2018) described the process by which the paper was created from bamboo fibers. A cooking kettle with a capacity of one thousand grams of oven-dried Ampel bamboo flakes was used to pulp flakes that had attained an air-dry moisture content. The ratio between bamboo granules and cooking solution (10.5% NaOH) was 1:8 (b/v). The pulping process lasted two hours at 100°C. After pulping, the soft bamboo flakes were separated from the remainder of the pulping solution (spent liquor) and washed with water until all pulping chemicals were removed and the pH was neutral. The obtained pulp was then processed into separated fibers on a Hollander beater at a consistency of 34% for 1 hour, resulting in a pulp fineness of 250–300 ml CSF (40–45° SR), a common value for sheet formation.

#### *Activated Carbon and Bamboo Paper-Activated Carbon Preparation*

Sawdust was carbonized at 400–500°C for 4–5 hours. The resultant charcoal is then activated for 70 minutes at 800°C using water vapor. The obtained activated charcoal was ground and then filtered through a 100-mesh screen. According to the Indonesian National

Standard (SNI 06-3730-1995), activated carbon (AC) that passed the 100-mesh filter was evaluated for its moisture content, ash content, volatile matter content, carbon content, crystallinity, and iodine absorption. Bamboo paper with activated nano-carbon (BPAC) was produced by combining 20% of the total fiber weight with 60 g/m<sup>2</sup> of activated carbon.

#### *In vitro Fungi Decay Experimental*

The bamboo papers were cut into fragments of 3 x 1 cm<sup>2</sup> and dried at 75°C for 48 hours; the weight of the paper after drying was recorded as the initial dry weight. The paper fragments were sterilized for 30 minutes in an autoclave at 121°C and 1 atm pressure. Two pieces of paper were put onto the surface of the PDA (Potato Dextrose Agar) plates, which have been overgrown with mycelia of either *Phlebiopsis* sp. or *Pycnoporus* sp.

The invitro decomposition trial consisted of two variables, viz. paper type (BPAC dan BPNAC) and fungal agents (*Phlebiopsis* sp. and *Pycnoporus* sp.), resulted in four treatment-combination, namely: (1) BPAC–*Phlebiopsis*; (2) BPAC–*Pycnoporus*; (3) BPNAC–*Phlebiopsis*; (4) BPNAC–*Pycnoporus*. Twelve repetitions for each treatment combination were carried out. The observation was conducted for 12 weeks at 4-week intervals. At each observation time,

the remaining dry weight ( $W_t$ ) of the paper was calculated using Eq. (1), in which  $W_0$  and  $W_n$  represent the dry weight of paper at the initial- and the pointed- observation time, respectively. In general, the mycelium completely covers the medium's surface in 7–10 days. The FPase activity was calculated based on the IUPAC method (Adney & Baker, 1996).

$$\% \text{ Wt} = \left( \frac{W_n}{W_0} \right) \times 100 \quad (1)$$

#### *Data Analysis*

Two-way Analysis of Variance (ANOVA) performed in IBM SPSS Statistics 24 was used to analyzed the paper's dry-weight loss data, which was then followed by Tukey's honestly significant difference (HSD) test to determine the mean differences of paper dry-weight loss during a gradual observation time.

### III. RESULT AND DISCUSSION

There were differences in degradation rate – indicated by the percentage of dry-weight reduction, between BPAC (bamboo paper with activated nano-carbon) and BPNAC (bamboo paper without activated nano-carbon), either those that have been degraded by *Phlebiopsis* sp. or *Pycnoporus* sp. (Figure 1). Based on the statistical analysis, the decrease of BPAC and

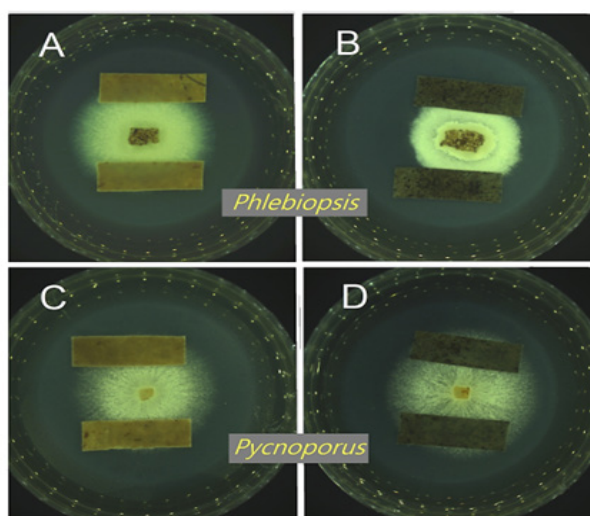


Figure 1. Invitro fungal decay tests at the 1<sup>st</sup> week of observation. (A). BPNAC by *Phlebiopsis* sp., (B). BPAC by *Phlebiopsis* sp., (C). BPNAC by *Pycnoporus* sp., (D). BPAC by *Pycnoporus* sp.



BPAC dry-weight in the 4<sup>th</sup>- and 8<sup>th</sup>- weeks was determined by the paper types (F-ratio = 17.01, p-value =  $1.62 \times 10^{-4}$ , HSD a=2.99; F-ratio = 10.28, p-value =  $2.5 \times 10^{-3}$ , HSD a=3.13, respectively) and fungal agents (F-ratio = 106.36, p-value =  $2.56 \times 10^{-13}$ , HSD b= 2.99; F-ratio = 386.71, p-value=  $2.01 \times 10^{-23}$ , HSD b = 4.18, respectively) but was not affected by the interaction between those two variables (Table 1). Influence of the interaction between these two variables (paper types and fungal agents) on the paper's dry-weight reduction was observed in the 12<sup>th</sup> week (F-ratio = 28.81, p-value =  $2.84 \times 10^{-6}$ , HSD ab =7.16, Table 1).

BPAC appeared to be more difficult to degrade compared to BPNAC, except for the samples that were degraded by *Phlebiopsis* sp. at the 12<sup>th</sup> week of observation (Figure 2), which showed that the dry-weight of BPAC ( $64.14 \pm 4.36$ ) was slightly lower than the BPNAC ( $69.87 \pm 2.90$ ). This phenomenon seems to be associated with microstructure changes and anti-microbial properties of the bamboo papers, which have been enriched by nanoactive carbon. The incorporation of activated carbon into the paper substrate has been seen to enhance the paper's ability to adsorb moisture, presenting a promising opportunity for the development of

a highly efficient humidity sensor (Kathiravan, Abayasekara, Kulasoorya, Wanigasekera, & Ratnayake, 2022). The findings of a separate study demonstrated that the incorporation of activated carbon into "Hanji" paper, a traditional Korean paper, resulted in enhanced characteristics of the paper as an electrode. The Hanji paper exhibits enhanced mechanical durability and effective penetration of activated carbons between its fibers using a one-pot procedure. This characteristic combination serves to prevent the electrode materials from leaching out of the paper and ensures the long-term stability of the electrode's capacitive properties (Kwon, Ryu, & Yim, 2021).

The findings of the aforementioned study demonstrate that incorporating activated carbon onto the paper substrate can enhance the characteristics of the paper, aligning with the objective of integrating activated carbon into the paper matrix. Indrawan et al. (2018) reported that BPAC, which was used for food packaging material, was proven to be able to maintain the freshness of the wrapped vegetables due to the anti-microbial effect of the paper. It seemed that the addition of AC has an inhibitory effect on the growth of microorganisms. Physical mode of bactericidal action, i.e., disruption of

Table 1. Summary of two-way analysis of variance at  $\alpha = 0.05$  for remaining paper weight during 12 weeks observation (4-week interval)

Time of Observation	Source	df	Sums of Squares	Mean Square	F-ratio	p-value
4 Weeks	Paper type	1	252.22	252.22	17.01	$1.62 \times 10^{-4**}$
	Fungal agent	1	1577.24	1577.24	106.36	$2.56 \times 10^{-13**}$
	Paper type * Fungal agent	1	2.22	2.22	0.15	0.70 <sup>ns</sup>
8 Weeks	Paper type	1	297.56	297.56	10.28	$2.50 \times 10^{-3*}$
	Fungal agent	1	11189.55	11189.55	386.71	$2.01 \times 10^{-23**}$
	Paper type * Fungal agent	1	0.10	0.10	0.00345	0.95 <sup>ns</sup>
12 Weeks	Paper type	1	73.83	73.83	2.62	0.11 <sup>ns</sup>
	Fungal agent	1	6575.17	6575.17	233.33	$3.34 \times 10^{-19**}$
	Paper type * Fungal agent	1	811.89	811.89	28.81	$2.84 \times 10^{-6**}$

Note: \*\* = significant at 1% test level, \* = significant at 5% test level, ns = non-significant

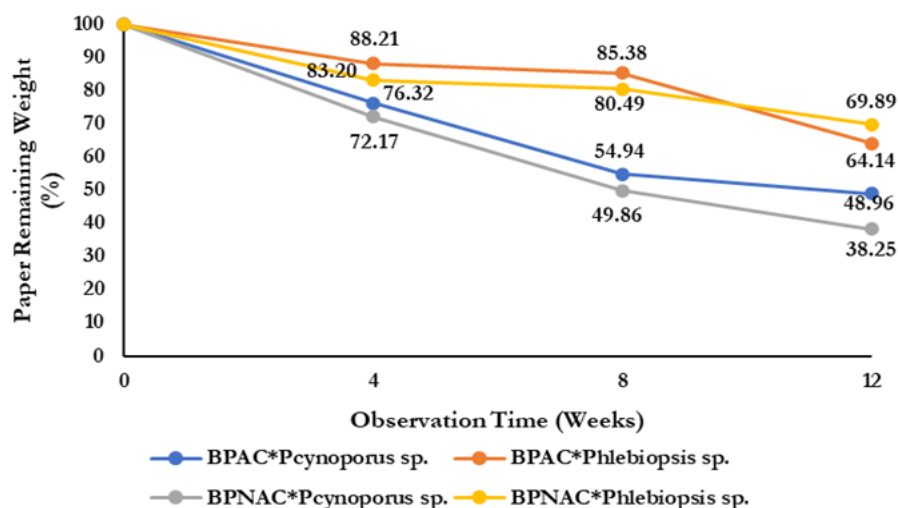


Figure 2. The bamboo paper's mass reduction by two white rot fungal species during 0 to 12 weeks of observation

the electron transport chain at the bacteria's cell membrane and induction of oxidative stress in the cytoplasm leads to the damage of bacteria's cell membrane (Mocan et al., 2017; Omerović et al., 2021) and impede the microbial growth on the packaging surface (Drago et al., 2020). Thus, it is understandable why the BPAC showed a lower decomposition rate compared to the BPNAC (Figure 2).

This study showed that the addition of nano-activated carbon (AC) has less influence on the bamboo paper degradability. Regardless of the species of fungal agents, the degradation rates of BPAC and BPNAC were slightly different (less than 5%). The average weight loss of BPAC was ranging from 18 – 43%, while BPNAC was 23–46%. Statistical analysis also proved that the effect of fungal agents on the degradation of bamboo paper was more prominent than the effect of paper type (Table 1). Contrary to this finding, Hastuti et al. (2021), who tested the biodegradability of BPAC and BPNAC in the composted soils, revealed that even though at the initial stage the carbonized papers were degraded slower than those without nano active carbon but at the end of observation 75% of BPAC's biomass was discharged and become part of the soil particles while the BPNAC 58%.

The different effects of nano-activated carbon on the decomposition of bamboo papers were related to the environmental conditions and biological agents applied in these two studies. This study was conducted in invitro conditions using a single fungal isolate, viz. *Phlebiopsis* sp. or *Pycnoporus* sp., while those that have been reported by Hastuti et al. (2021) were soil-inhabited microbial consortia – consisting of *Scedosporium apiospermum*, *Pseudomonas aeruginosa*, *Pycnoporus sanguineus*, and *Bacillus* sp. The first study was carried out in an axenic condition using single species of microbes, while the second study was conducted in a more complex condition – using composted soil as a growth medium as well as a source of decomposer agents. So, it is sensible if these studies showed different results, even though they used a similar composition of paper materials to be tested. The presence of AC in the soil may encourage the microbial consortium to grow and induce a more complex biochemical activity of soil-dwelling fungi in response to the environmental condition (Taskin et al., 2019). Surely, the biodegradation phenomenon under more complex conditions will not be the same as those under the simple one.

The two white rot fungi used in this study showed different rates of degrading the same paper-type materials. *Pycnoporus* sp. showed its superior degradability against *Phlebiopsis* sp. in discarding both BPAC and BPNAC. The degradation rate of these two types of bamboo papers induced by *Phlebiopsis* sp. and *Pycnoporus* sp. were illustrated in Figure 1. At the first 4 weeks, *Pycnoporus* sp. degraded approx. 24–27% the bamboo papers, while *Phlebiopsis* sp. 12–17%. Up to eight weeks of observation, about half of the bamboo paper mass (45–50%) has been digested by the fungal *Pycnoporus* sp. After 12 weeks of observation, the remaining BPNAC mass degraded by *Pycnoporus* sp. was significantly lower compared to the other treatment combination. It can be concluded that *Pycnoporus* was able to decompose bamboo paper by >50%, while *Phlebiopsis* was only  $\pm$  30% (Figure 3).

The superiority of *Pycnoporus* isolate in digesting the bamboo papers compared to *Phlebiopsis* isolate is associated with the activity of enzyme properties (cellulases complex) excreted by the fungus. Cellulases are extracellular inducible enzymes, which means they are synthesized by the cells and excreted into the environment in response to the type of cellulose acting as a growth medium for the microorganisms (Ortega, Busto, & Perez-Mateos, 2001). In this study, papers are the

media used to induce cellulases produced by the fungi, and usually, filter papers are used as a standard media. So, filter paper-ase (FPase) is the common term used for the excreted cellulase complex. The value of FPase activity indicates the level and characteristics of the cellulases produced by degrading microorganisms (Lee et al., 2011; Bergadi et al., 2014). Measurement of FPase activities produced by *Phlebiopsis* sp. and *Pycnoporus* sp. during the bamboo-paper degradation and their comparison to filter paper degradation is presented in Figure 4.

Figure 4 showed that *Pycnoporus* sp. showed greater FPase activities compared to *Phlebiopsis* sp. in all types of papers used in the study. *Pycnoporus* sp. exhibited FPase activity ranging from 0.38–0.57 FPU, *Phlebiopsis* sp. ranging from 0.12–0.23 FPU. FPase activity is associated with the degradation rate of the paper (Liu et al. (2012). The higher the FPase activity value, the faster the degradation rate occurred.

The superiority of the FPase produced by *Pycnoporus* over the FPase produced by *Phlebiopsis* was consistently observed, even when the fungi were cultivated using various media. Kathirgamanathan et al. (2017), who used rice bran, corn cobs, and paper as the cultivation media, reported that *Pycnoporus* sp. excreted FPase with higher activity than those produced by *Phlebiopsis* sp. It was revealed that *Pycnoporus* possessed a potential application to degrade

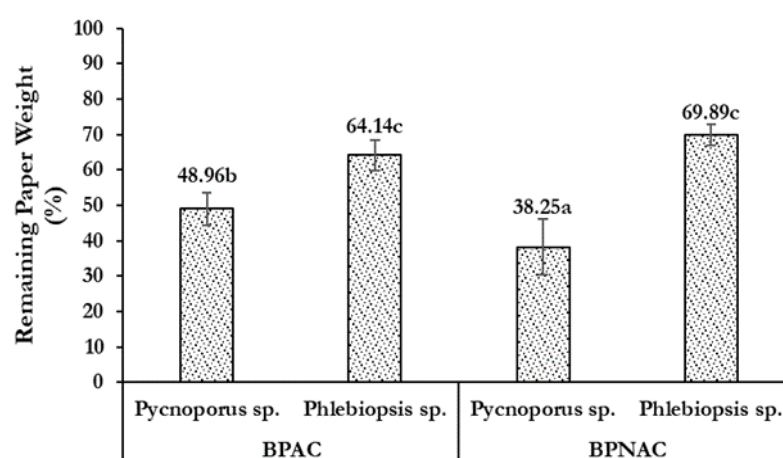


Figure 3. Degradability of two white rot fungi species towards two types of bamboo papers at 12 weeks observation. The values followed by different alphabets showed significant differences

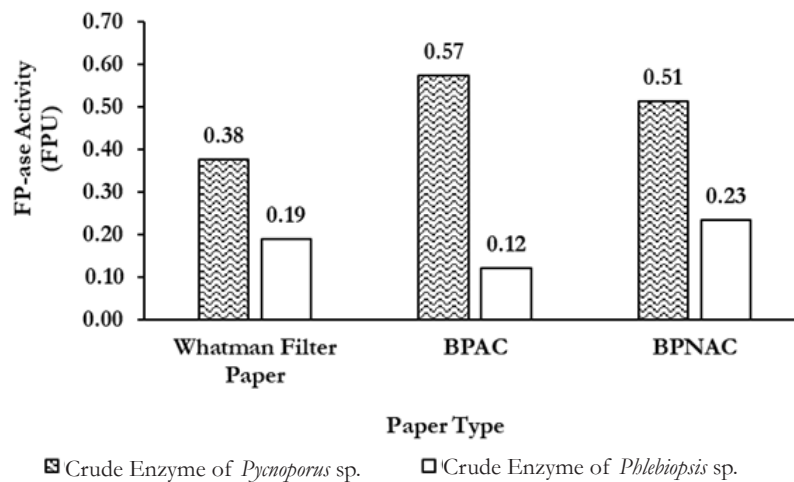


Figure 4. FPase activities of *Pycnoporus* sp. and *Phlebiopsis* sp. digesting three different types of papers

Table 2. Invitro degradation rates of bamboo papers compared to other commercial papers

Fungsi species	Degradation rate (mg/week cm <sup>2</sup> )				
	BPAC	BPNAC	Cardboard*	Tissue paper*	Newspaper*
<i>Pycnoporus</i> sp.	0.03	0.06	-	-	-
<i>Phlebiopsis</i> sp.	0.02	0.03	-	-	-
<i>Trichoderma viride</i> *	-	-	1.02	0.54	0.34

Source: \* Belal (2008)

various lignocellulosic materials. Furthermore, through comparing FPase activities produced by several fungal isolates, *Pycnoporus* sp. consistently showed its superiority compared to other isolates. Bergadi et al. (2014) who study cellulase activities of microflora isolated from old manuscripts reported that FPase activities of *Aspergillus niger*, *A. oryzae*, *A. melleus*, *Hypocrea lixii*, *Mucor racemosus*, *Schizophyllum commune*, and *Penicillium chrysogenum* were ranging from 0.03 to 0.06 FPU, while the *Pycnoporus* enzyme was 0.38 FPU. Thus, it could be interpreted that *Pycnoporus* sp. was one of the fungal species with high potential application for degrading lignocellulosic materials.

In comparison to a similar study about paper packaging degradation, degradation of the bamboo composite papers (BPAC) conducted in this study is considered less effective. In 12 weeks, about 62% and 75% of BPAC mass have been degraded with the initiation of white rot fungi *Pycnoporus* sp. and composted soils, respectively. Meanwhile, Nowińska et al. (2019),

who studied packaging paper degradation in the soil (with and without biochar) recorded that the papers were degraded by 35% and 60%, respectively, after only a 4-week experiment. This means that improvement in BPAC degradation methods is still required.

One of the efforts that can be promising is by applying other fungal isolates, e.g., *Trichoderma viride*, which has been characterized as having high cellulase enzyme activity (Belal, 2008). The ability of *T. viride* to degrade paper packaging was substantially faster than *Pycnoporus* sp. and *Phlebiopsis* sp. (Table 2). The higher enzyme activity of *T. viride* caused a higher degradation degree of paper. The degradation degree of paper packaging by *Trichoderma viride* was around 75% after 3 weeks of decay test (Belal, 2008). *Pycnoporus* sp., formerly considered a potential fungal isolate for degrading bamboo packaging paper, seems less effective compared to the ability of *T. viride*. As the biodiversity of degrading organisms is divergent, which means their ability to degrade particular



substances is diverse depending on the species and the environment where they had been collected (Lintang et al. 2021), research to look for microorganisms that can optimize the degradation of nano-carbonized bamboo paper and also other composite materials are needed to be continued.

In accordance with the concern about waste management of bamboo paper composite, findings of this study, as well as results from a previous study conducted by Hastuti et al. (2021), indicate that the BPAC as an alternative food packaging is prospective to be developed in the future without worrying about its degradation process. Even though the addition of active nano-carbon improved the structure and quality of the bamboo papers, its degradation procedure is still can be accelerated by applying microbial consortium (in the form of composted soil) and/or single fungal isolate (such as *Pycnoporus* sp.). However, as this result is still un-optimum and the application of the degradation technique on a large scale requires a particular microbial consortium formula that can accelerate the degradation process as well as ensure that any potential risks and threats are manageable, further studies on searching for more potential microbial agents and designing power plant for the waste decomposition are strongly encouraged.

#### IV. CONCLUSION

The addition of activated nano-carbon into the bamboo papers has insignificant effects on the paper's degradability. By assessing the degradation rate and its enzymatic activity, *Pycnoporus* sp. is more promising to be applied as a fungal-decomposer agent for nano-carbonized bamboo papers rather than *Phlebiopsis* sp. However, as the effectiveness of these fungal decomposer agents is still under the expectation, research on exploring and testing other microbial formulas to enhance the degradation rate and any related study for more effective and efficient waste management is recommended.

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