Physical and Mechanical Properties of Mycelium-based Insulation Materials Produced from Desilicated Wheat Straws - Part A

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Mycelium-based insulation materials made from lignocellulosic resources have the potential to replace petroleum-based foams. In this study, desilicated wheat straw was inoculated with *Pleurotus ostreatus* (PO) and *Ganoderma lucidum* (GL) fungi and incubated for 10, 20, and 30 days to produce mycelium-based insulation boards. The process of extracting silica from wheat stalks was conducted using a 1% sodium hydroxide (NaOH) solution prior to the production of mycelium-based insulation boards. Density, water absorption, thickness swelling, modulus of rupture, modulus of elasticity, tensile strength perpendicular to the surface (Internal bonding test), and compressive strength of the mycelium insulation boards were measured. The results showed that mycelium-based insulation boards produced with GL had better physical and mechanical properties than those produced with PO. Furthermore, pretreatment of wheat straw with 1% NaOH improved the mechanical properties of the insulation boards produced.

DOI: 10.15376/biores.19.1.1330-1347

Keywords: Mycelium-based insulation materials; Wood decay fungi; Bioengineered materials; Technological properties; Wheat straw

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INTRODUCTION

Styrofoam, foam, and other commonly used insulation materials are usually composed of petroleum-based materials. Commonly used insulation materials have several disadvantages, *i.e.*, they are flammable, carcinogenic, and non-biodegradable. Polymeric foam derived from petroleum pollutes the environment by emitting organic compounds including benzene and styrene (Bruscato *et al.* 2019). The limitations of existing petroleum-based insulation materials can be eliminated or reduced by replacing these materials with non-polluting, biodegradable biomaterials with lower economic and environmental impact.

The strength values of insulation boards made from mycelium-based materials and petroleum-based foams can vary depending on the specific formulations, manufacturing processes, and intended applications. However, it can be concluded that the mechanical properties of the foams in general are higher than the mycelium-based insulation boards. The mechanical properties of the foams are presented in Table 1 (ASTM C578-04; Yildirim 2018).

Table 1. Mechanical Properties of Foams

	Density (g/cm^3)	Water Absorption (%)	Elastic Modulus (kPa)	MOR (kPa)	Tensile Strength (kPa)	Compressive Strength (kPa)	Ref.
Foamular® 150	0.03	-	21610.18	497.82	-	224.36	Yıldırım 2018
GreenGuard®	0.04	-	18454.16	317.86	-	226.52	
Styrofoam™	0.04	-	65915.39	391.09	-	213.05	
EPS	0.029	4	-	70	96	35	ASTM C578–04

Mycelium-based products possess several benefits in comparison to other lignocellulosic materials, such as molded paper pulp structures. Mycelium-based composites demonstrate excellent structural integrity and strength. The mycelium functions as a natural adhesive, effectively joining the substrate material and creating a strong and durable structure. This can lead to the production of materials that possess competitive or superior strength in comparison to certain other lignocellulosic materials. Fungal materials are typically characterized by their low density, making them particularly suitable in situations where weight is a crucial factor. This attribute arises from the permeable composition of the structures formed by the mycelium. The growth conditions and substrate composition throughout the cultivation phase can be modified to tailor fungal materials for specific purposes. This adaptability enables customization of characteristics such as density, strength, and insulating capability. Fungal materials have biodegradable properties, rendering them more ecologically favorable compared to some alternative materials. They have the ability to undergo natural decomposition, hence minimizing their environmental footprint at the conclusion of their life cycle. Mycelium-based materials exhibit favorable thermal and acoustic insulation characteristics, rendering them well-suited for insulation purposes. The mycelial network forms an inherent obstacle to the transfer of heat and sound. Through the cultivation process, fungal materials can be shaped and molded into diverse and sophisticated designs, offering the possibility of creating unique forms. The ability to adapt is beneficial for producing items with intricate shapes. The synthesis of fungal materials generally requires less energy compared to the processing of some other lignocellulosic materials, such as those utilized in the construction of paper pulp structures. Fungal materials can be cultivated on agricultural or industrial waste, thereby converting these materials into valuable commodities. This has the potential to facilitate waste reduction and enhance resource efficiency. Although fungal materials possess these benefits, the selection between fungal materials and other lignocellulosic materials is contingent upon the specific demands of the application, cost factors, and material accessibility. Every material possesses a distinct array of attributes that can render it more appropriate for specific applications.

The kingdom of fungi is one of the most diverse groups of eukaryotic organisms on Earth. Fungi play fundamental ecological roles as decomposers, mutualists, or pathogens. The global fungal diversity is estimated at 0.8 million to 5.1 million species; however, only about 120,000 species have been described.

Fungi are unicellular, multicellular, or syntactic organisms that produce spores and feed on organic matter (Hawksworth 2001; Webster and Weber 2007; Blackwell 2011; Tedersoo *et al.* 2014).

White-rot fungi, or wood-decay fungi, are essential global regulators of the carbon cycle. In nature, lignin is broken down by white-rot fungi. The delignification of wood by white-rot fungi can be selective or non-selective. In selective delignification, lignin is degraded before hemicellulose and cellulose. In non-selective delignification, all components of the cell wall are simultaneously degraded (Eriksson *et al.* 1990).

Hypha is a structure of microscopic strands of fungal cells joined end to end. The network of hyphae is called a mycelium. Under normal ambient conditions, the hyphae degrade and adhere to the surface of organic materials without additional energy input. The hypha consequently acts like a natural self-adhesive glue. It has properties of structural binding through the growth of the hyphae in the structure of the mycelia and the expansion of the network structure. Chitin and oligosaccharide-based beta-glucans found in the fungal cell wall are also thought to be responsible for increasing adhesion/binding (Wesenberg *et al.* 2003; Narayanaswamy *et al*. 2013; Sauerwein *et al*. 2017; Abhijith *et al.* 2018; de Paula *et al*. 2019). Compared with synthetic fibers, mycelia have some key advantages, *i.e.*, they have low density, are cost-effective, require less energy during production, and probably most importantly are biodegradable (Arifin and Yusuf 2013; Haneef *et al*. 2017; Abhijith *et al*. 2018).

Mycelium growing on lignocellulosic and waste materials has garnered the interest of researchers to develop low-energy construction materials and waste recycling approaches (Madurwar *et al*. 2013). Mycelia bind organic matter through a network of hypha microfilaments in a natural biological process that can be used to produce both low-value materials including packaging and higher-value composite materials (Pelletier *et al*. 2013; Haneef *et al*. 2017; Jones *et al*. 2017) from poor agricultural products and industrial waste materials with little or no commercial value (Bhuvaneshwari *et al*. 2019).

Many low-quality lignocellulosic materials, such as agricultural by-products and agricultural wastes, have been used to produce mycelium-based composites because they are inexpensive. However, agricultural by-products and wastes contain significant amounts of minerals, such as silica, which inhibits fungal growth (Nasreen *et al.* 2016; Jones *et al*. 2019a; Elsacker *et al.* 2022). Jones *et al*. (2019b) reported that the inhibition of fungal growth led to weaker bonding between lignocellulosic particles/chips and worse mechanical properties of mycelium-based composites.

Many researchers have produced mycelium-based composites using wheat straws and other agricultural plants and performed studies to determine their physical and mechanical properties. However, to the best of the authors' knowledge, no study has attempted to determine the physical and mechanical properties of mycelium-based composites produced from desilicated wheat straws. The hypothesis of the present study was that the removal of silica by desilication pre-treatment of wheat straw will both be a suitable substrate for the growth of mycelia and improve the mechanical properties of the produced mycelium-based insulation boards.

This study aimed to determine the mechanical and physical properties of mycelium-based insulation boards produced from desilicated wheat straw incubated with PO and GL fungi for 10, 20, and 30 days. In addition, the effects of fungus species and incubation durations on the physical and mechanical properties of mycelium-based insulation boards produced from desilicated wheat straw.

EXPERIMENTAL

Materials

In this study, wood-decaying *Pleurotus ostreatus* (Jacq.) P. Kumm. (Mad-542-Sp) (PO) and *Ganoderma lucidum* (Curtis) P. Karst. (CS-70-11A) (GL) fungal cultures were obtained from Northern Research Station United States Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA.

Wheat straw obtained from Kalaycıoğlu Ticaret (Trabzon) was used to produce mycelium-based insulation material.

The wheat straw supplied was Algemaier brand wheat straw that was passed through a 10-mm single-stage sieve with circular motion. Total dry weights of the prepared wheat straws were determined.

Production of mycelium-based insulation boards

The silica components typically present in wheat straw were removed using pre-desilication before exposure to fungal incubation. Pre-desilication was performed by treating wheat straw in 1% NaOH solution at 50 °C for 20 min (Deniz 1994). The NaOH reacts with silica in the wheat straw to form sodium silicate, which is soluble in the alkaline solution (Hurter 1998; Tutus and Eroglu 2004). After the desilication process, the wheat straws were filtered through a sieve and thoroughly washed with water until the chemicals were removed. The samples were laid out and dried in open air at a humidity of 70% to 80%.

The moisture content of the wheat straws, whose full dry weight was determined, was adjusted to 70% to 80%, and the pH was adjusted to 7. The straws were then sterilized in heat-resistant polyethylene bags in an autoclave at 121 °C for 30 min and allowed to cool in a sterile environment. The cooled samples were inoculated with the prepared grain inoculum (10% w/w) of each fungus used in this study. After inoculation, the wheat straws in the bags were placed in a climate cabinet. The climate cabinet was set to 25 °C and 70% relative humidity and incubation periods were started. Production variables of mycelium-based insulation boards are shown in Table 2.

Table 2. The Production Plan of Mycelium-based Insulation Boards

Board Types	Fungal Types	Lignocellulosic Feedstock	Incubation Duration (Day)
YG1	GL	Wheat straw	$7^a + 3^b$
YG2			$15^a + 5^b$
YG3			$25^a + 5^b$
YP1	PO		$7^a + 3^b$
YP2			$15^a + 5^b$
YP3			$25^a + 5^b$

[a]: Incubation duration before wheat straw was placed in molds; [b]: Incubation duration after wheat straw was placed in molds

At the end of the 7th day, a sufficient amount of bagged wheat straw was collected from the climate cabinet and placed on 300 × 300 × 40 mm^3 plastic molds and left in the climate cabinets again and the 10th-day incubation period was completed. At the end of the incubation period, straws were removed from the plastic molds and dried in a drying oven set at 90 °C. The same procedure was performed on day 15 and day 25 for mycelium-based insulation boards with incubation periods of 20 and 30 days, respectively (Fig. 1). Five boards were produced for each variation group.

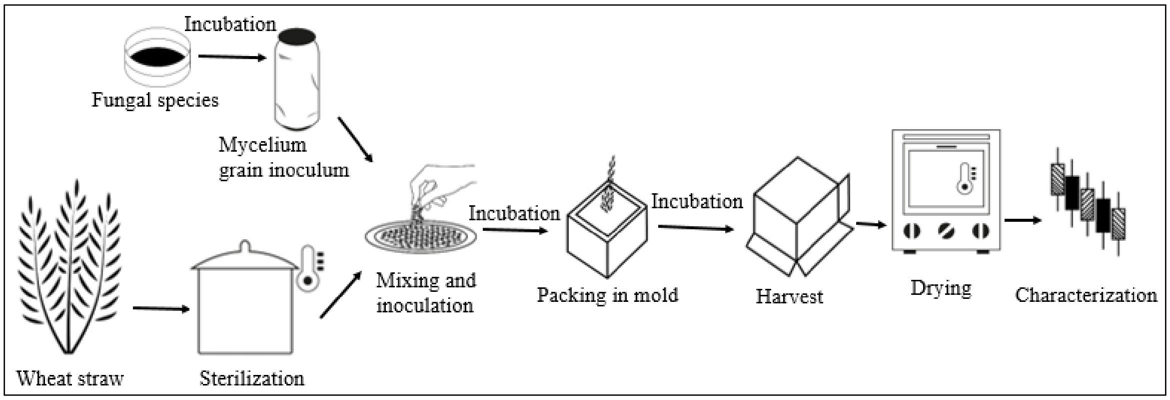


Fig. 1. The production process for mycelium-based insulation boards

Test Standards

Determination of technological properties of mycelium-based insulation boards

Prior to testing, all specimens were conditioned in a laboratory for at least 3 weeks at room temperature (25 °C) and 65% relative humidity. The density of each group of insulation board was measured using samples with dimensions of 50 mm × 50 mm board thickness, following the guidelines outlined in ASTM C303-02 (2012). A total of 10 replicate test samples were utilized for each test.

The water absorption (WA) and thickness swelling (TS) of each set of insulation boards were assessed using samples with dimensions of 50 mm × 50 mm board thickness, in accordance with the guidelines outlined in ASTM D1037 (2012). The specimens were submerged in distilled water, and the weights and volumes were recorded at 1.5 h and 168 h. The water absorption and thickness swelling values were calculated by comparing the weight and volume differences to the initial measurements of weight and volume. In each trial, a total of 10 test samples were employed.

The values for the modulus of rupture (MOR) and the modulus of elasticity (MOE) were obtained in accordance with the ASTM C203-05a (2012) standard, with certain adjustments made during the testing process using a Zwick Roell Z050 universal testing machine. The MOR and MOE experiments were conducted on rectangular specimens with dimensions of 300 × 50 mm^2. The specimens were subjected to a span of 240 mm and a crosshead speed of 3 mm/min. A total of 10 replicate test samples were utilized for each test.

The tensile strength perpendicular to the surface test (internal bond strength-IB) was determined according to EN 319 (1993) with modifications using a Zwick Roell Z050 universal testing machine. The tensile strength perpendicular to the surface test was carried out by bonding samples with a sample size of 50 × 50 × board thickness (mm^3) with the surface effectively bonded onto an aluminum loading block using hot-melt glue. After curing, the loading block was set into the grip and a tensile force was applied with a speed of 2 mm/min. The internal bond strength was calculated. For each test, 10 (replicate) test samples were used.

The determination of compressive strength (CS) was conducted in accordance with the ASTM C165 (2012) standard, with certain adjustments implemented using a Zwick Roell Z050 universal testing machine. The material under examination was prepared ahead of time with standard dimensions of 50 mm × 50 mm × the thickness of the board. The dimensions of the tested material were 50 mm × 50 mm × the thickness of the board. A compressive force was applied to the material at a speed of 2 mm/min. According to the ASTM C165 (2012) standard, the compressive strength of the specimen was determined at an elongation of 10% of its geometry. A total of 10 test samples were utilized for each test, ensuring replication.

Statistical analysis of the data obtained was performed using a statistical package program (IBM SPSS v22, Armonk, NY, USA). All analyses were performed at 95% confidence level. Differences between the experimental groups were determined *via* one-way analysis of variance and multivariate analysis of variance. In case of significant differences between the experimental groups, *post hoc* tests were performed based on the homogeneity of the groups.

RESULTS AND DISCUSSION

Results

The silica contents of the wheat straws subjected to pre-desilication, and wheat straws not subjected to pre-desilication (control) within the scope of the study are presented in Table 3. Analyses of the findings revealed that the control wheat straw contained 5.24% silica, whereas the desilicated wheat straw contained 3.14% silica. It was found that approximately 35% of the silica content in the wheat straw was removed.

Table 3. Silica Contents of Wheat Straw

Species	Silica Content (%)
Control wheat straw	5.24 ± 0.26
Desilicated wheat straw	3.41 ± 0.17
± Indicates standard deviations	

Investigation of Physical and Technological Properties of Mycelium-based Insulation Boards

Density values of mycelium-based insulation boards

The density values of the produced mycelium-based insulation boards are presented in Table 4. The density values of the boards ranged between 131 and 141 kg/m^3.

Water absorption and thickness swelling of mycelium-based insulation boards

Water absorption (WA) and thickness swelling (TS) of the produced mycelium-based insulation boards are presented in Table 4.

Table 4. Homogeneity Groups of Physical Properties Depending on GL and PO Fungus Types

Board Types	D (kg/m^3)	WA (%) 1.5 h		WA (%) 168 h		TS (%) 1.5 h		TS (%) 168 h	
YG1	135 ± 0.06	64.47 ± 5.80	A*	250.66 ± 8.04	F	2.91 ± 0.54	A	5.60 ± 0.80	A
YG2	134 ± 0.08	65.74 ± 4.60	A	223.40 ± 7.90	G	3.58 ± 0.97	AB	6.34 ± 0.77	AB
YG3	137 ± 0.12	96.52 ± 5.89	B	247.71 ± 9.37	FG	2.44 ± 0.79	AC	4.45 ± 0.82	AC
YP1	141 ± 0.15	66.82 ± 3.12	AC	135.54 ± 6.97	H	5.37 ± 0.27	ns	6.91 ± 0.89	ns
YP2	131 ± 0.07	51.12 ± 5.25	D	141.83 ± 9.45	H	4.11 ± 0.79	ns	5.87 ± 0.95	ns
YP3	132 ± 0.12	85.37 ± 8.29	BE	177.03 ± 8.44	I	4.39 ± 1.02	ns	6.07 ± 0.45	ns

*Different letters indicate a significant difference within the same group, ns: not significant, ± indicates standard deviations

The WA rates of insulation boards produced with two different fungi species and three incubation periods increased rapidly in the first 3 h, then followed a relatively horizontal course until 24 h, and then increased rapidly after 24 h. The maximum WA rates of the boards produced using PO species were lower than those produced using GL species at the end of 168 h. The WA rates of mycelium-based boards produced from wheat straws inoculated with PO fungus and incubated for 20 and 30 days (YP2 and YP3) were lower than those of the other boards produced in this study.

The TS rates of the boards produced with two different fungi species and three incubation periods increased rapidly in the first 3 h, then followed a relatively horizontal course until the end of the test duration. The highest TS rate was obtained in the YP1 group boards while the lowest TS rate was determined in the YG3 boards. However, incubation duration did not have significant effects on the TS rates of the mycelium-based insulation boards produced using PO fungus in this study (Table 4).

Investigation of Mechanical Properties of Mycelium-based Insulation Boards

Results from MOR, MOE, IB, and CS

The MOR, MOE, and IB values of the insulation boards are given in Table 5. For all three incubation periods, insulation boards produced with GL fungus had higher MOR and MOE values than those produced with PO fungus. YG2 mycelium-based insulation boards produced from wheat straw inoculated with GL fungus and incubated for 20 days had the highest MOR and MOE values. YP3 mycelium-based insulation boards produced with wheat straw inoculated with PO fungus and incubated for 30 days had the lowest MOR and MOE values. Although the incubation duration had a significant effect on the MOR of the boards produced with PO fungus, there was no significant effect on the MOR of the boards produced with GL fungus. In addition, incubation duration did not have a significant effect on the MOE of the boards produced with both PO and GL fungi.

Table 5. Homogeneity Groups of Mechanical Properties Depending on GL and PO Fungus Types

Board Types	MOR (kPa)		MOE (kPa)	IB (kPa)		CS at 10% Deformation (MPa)	
YG1	116.23 ± 48.58	ns	3597.50 ± 1441.63	11.56 ± 1.68	A	0.65 ± 0.14	A
YG2	138.19 ± 49.14	ns	5642.50 ± 2552.11	17.41 ± 1.73	B	0.54 ± 0.08	AB
YG3	109.88 ± 31.57	ns	5376.67 ± 2506.13	18.61 ± 3.96	B	0.48 ± 0.07	B
YP1	55.86 ± 25.42	AB*	4498.57 ± 2015.25	6.50 ± 0.80	ns	0.36 ± 0.10	ns
YP2	64.77 ± 29.11	A	5667.14 ± 2484.81	7.68 ± 1.81	ns	0.30 ± 0.08	ns
YP3	35.4 ± 9.47	B	3931.43 ± 1114.79	6.21 ± 0.74	ns	0.36 ± 0.08	ns

*Different letters indicate a significant difference within the same group, ns: not significant, and ± indicates standard deviations

The findings obtained regarding the tensile strengths of mycelium-based insulation boards perpendicular to the surface are given in Table 5. YG3 mycelium-based insulation boards produced from wheat straw inoculated with GL fungus and incubated for 30 days had the highest IB values. YP3 mycelium-based insulation boards produced with wheat straw inoculated with PO fungus and incubated for 30 days had the lowest IB values. While the incubation duration had a significant effect on the IB values of the boards produced with GL fungus, incubation duration did not have a significant effect on the IB values of the boards produced with PO fungus.

The findings obtained regarding the CS values of mycelium-based insulation boards at 10% deformation are given in Table 5. The CS values of the insulation boards produced using GL fungus were higher than those produced using PO fungus. YG1 mycelium-based insulation boards produced from wheat straw inoculated with GL fungus and incubated for 10 days had the highest CS values. YP2 mycelium-based insulation boards produced with wheat straw inoculated with PO fungus and incubated for 20 days had the lowest CS values. The impact of the incubation period on the internal bond (IB) values of boards manufactured with GL fungus was statistically significant. However, no statistically significant effect of incubation duration on the IB values of boards produced with PO fungus was observed (Tables 5 and 6).

Table 6. Variance Analysis of Physical and Mechanical Properties of Mycelium-based Isolation Materials

Fungal Types	WA	TS	MOR	MOE	IB	CS
GL	***	***	ns	ns	***	***
PO	***	ns	***	ns	ns	ns

ns (not significant), *** (significant at $\alpha < 0.001$)

Discussion

Density values of mycelium-based insulation materials

Mycelium-based insulation boards produced after inoculation of wheat straw with PO fungus and incubation for 10 days (YP1) had the highest density value, whereas insulation boards produced after incubation for 20 days (YP2) had the lowest density value. The density of mycelium-based composite materials produced from agricultural waste (including straw and annual plant straw) reportedly ranged between 60 and 300 kg/m^3

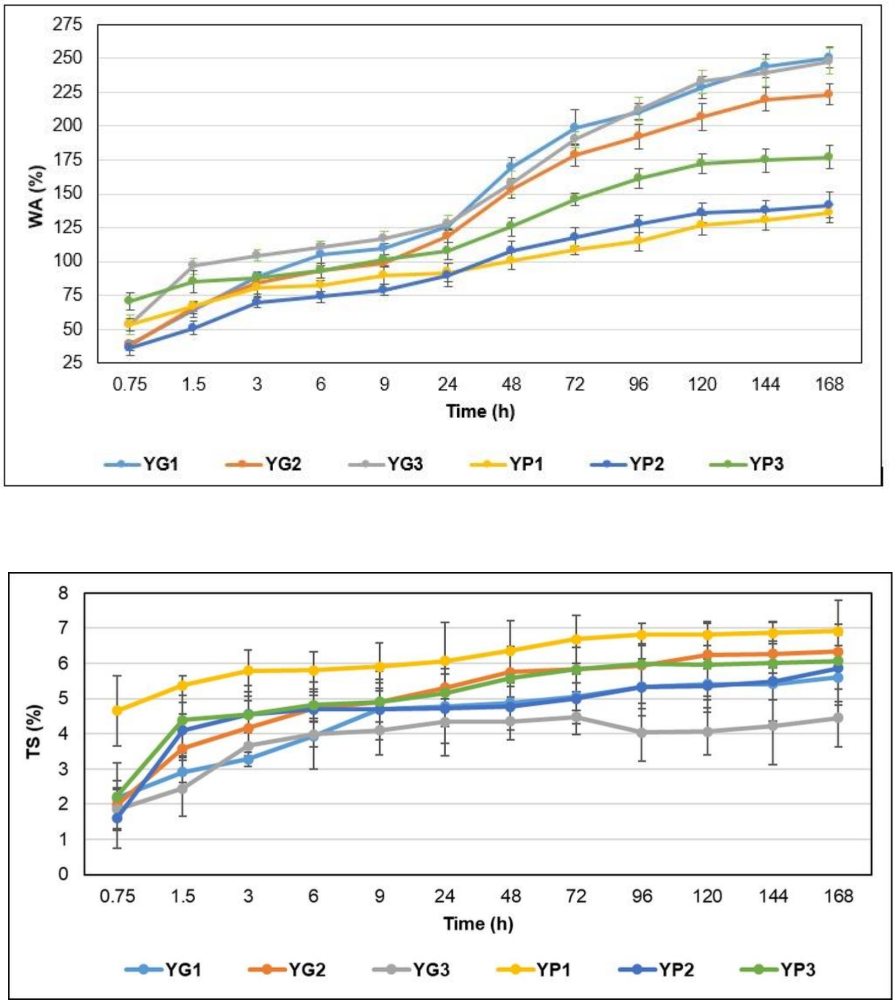
(Elsacker *et al*. 2019; Ghazvinian *et al*. 2019). Ghazvinian *et al*. (2019) reported that the density of mycelium-based composite materials produced from wheat straw varied between 192 and 277 kg/m^3.

Investigation of WA and TS of mycelium-based insulation boards

The high WA rates of mycelium-based composite materials are reportedly one of their biggest drawbacks. Mycelium composites are typically hygroscopic and have been reported by many researchers to increase in weight approximately 40% to 580% when in contact with water for 48 to 192 h (Holt *et al*. 2012; López Nava *et al*. 2016; Appels *et al*. 2019; Elsacker *et al*. 2019; Sun *et al*. 2019). The strong WA affinity of mycelium-based composites was reported to be the result of typical cellulosic filler components containing many accessible hydroxyl groups (Zabihzadeh 2010) and hydrophilic porous mycelium binder and biologically derived filler phases (Li *et al*. 2013; Wei *et al*. 2015) that promote wicking. Appels *et al*. (2019) inoculated *Trametes multicolor* and PO fungi into rapeseed chaff, low-quality cotton fibers, and beech wood sawdust, produced mycelium-based composite materials with or without pressing, and reported WA values ranging from 43% to 508% after 198 h. They reported that the composite material with the lowest WA was the one produced by inoculating beech wood sawdust with *T. multicolor* fungus and without pressing, whereas the highest WA was observed in the material produced by inoculating rapeseed straw with *T. multicolor* fungus and using hot pressing.

Elsacker *et al.* (2019) inoculated straw with *Trametes versicolor* fungus and determined that the WA rate of the mycelium-based composite materials produced without pressing was 26.8% at the end of 24 h.

In the present study, the WA rate of mycelium-based insulation boards produced using desilicated wheat straws was relatively lower than that of mycelium composites produced by other researchers using various substrates, fungi, and incubation intervals (Holt *et al*. 2012; López Nava *et al.* 2016; Appels *et al*. 2019; Elsacker *et al*. 2019; Sun *et al*. 2019). The reason for this could be due to the better formation of the mycelial mat on the boards' surface that reduces/blocks water uptake as a result of better and denser growth of fungal mycelium due to the silica removal process applied on wheat straw. It is important to acknowledge that the water absorption (WA) rates of mycelium composites are influenced by various aspects, including the substrate used, the type of fungus employed, the manufacturing technique (cold or hot press), the density of mycelium composites, the time of incubation, and the specific method utilized for measuring WA values. This circumstance presents a significant challenge when attempting to conduct a comparative analysis of the water absorption rates exhibited by mycelium composites developed by other researchers.



Error bars show standard deviation.

Fig. 2. Effect of fungal types and incubation time of physical properties on mycelium-based isolation materials

While the substantial absorption of water may appear to offer a considerable challenge for certain construction applications of mycelium composites, it is fortunate that these materials may be effectively utilized for internal or dry places, such as acoustic or thermal insulation, where they are not exposed to environmental elements. This helps to alleviate the otherwise noteworthy issue associated with water uptake.

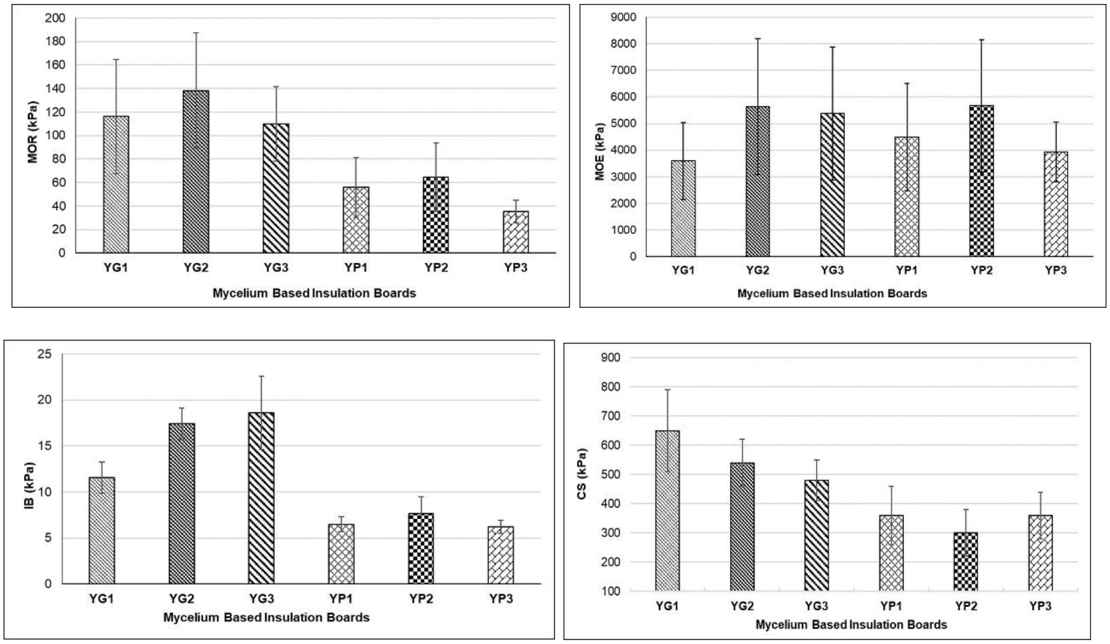
Examination of the TS results of the mycelium-based insulation boards produced within the scope of the present study revealed that the TS values of the boards were quite low despite their high WA rates (Fig. 2). This indicated that the absorbed water was free water due to the high void ratio in the boards because the boards were produced without any pressing procedure and their relatively low density. Indeed, fungal mycelia and hyphae exhibit water-repellent properties and play a role in the dimensional stabilization of the produced mycelium-based composite materials and/or the limited TS rates of the boards. Studies have reportedly examined WA values of mycelium-based composite materials; however, to the best of the authors' knowledge, no study has examined TS rates.

Investigation of mechanical properties of mycelium-based insulation boards-Analysis of MOR, MOE, IB and CS values

The MOR, MOE, IB, and CS values of the mycelium-based insulation boards are given in Fig. 3. Based on the observation that the highest MOR and MOE values were achieved after a 20-day incubation period, it was concluded that the optimal duration for incubation was 20 days. The removal of silica, a known inhibitor of fungal growth, was hypothesized to enhance the mechanical properties of mycelium-based insulating boards, namely the MOR and MOE. This enhancement was attributed to improved growth of fungal mycelia, enhanced bonding between fungal mycelia and wheat straws, and a more intricate network structure of fungal mycelia. The reason for the decrease in the MOR values of mycelium-based insulation boards with increasing incubation time was attributable to the destruction of the chemical main components (lignin, hemicellulose, and cellulose) of the lignocellulosic material (wheat straw) by the fungi used in the study (Appels *et al*. 2019; Gan *et al*. 2022; Kuştaş 2022). Appels *et al*. (2019) determined the MOR and MOE of mycelium-based composites produced from straw inoculated with *T. multicolor* and PO fungi and incubated for 14 days. They found that the MOR and MOE of mycelium-based composites were 0.22 MPa and 0.06 MPa and 4 MPa and 2 MPa, respectively. Gan *et al*. (2022) produced mycelium-based composites from bamboo fibers inoculated with PO and incubated for 28 days. The mycelium-based composites were reported to reach the highest MOE value (250 kPa) at 15 days and the MOE value decreased as the incubation duration increased. The decrease in the MOE with increasing incubation time was attributed to the decomposition of the bamboo fibers by the fungi.

In the present study, the MOR and MOE values of mycelium-based insulation materials produced using desilicated wheat straw were significantly higher than those reported in previous studies. Removing silica, which inhibits/limits fungal growth, was thought to increase the MOR and MOE values of mycelium-based insulation boards due to better development of fungal mycelia, better bonding between fungal mycelia and wheat straws, and more developed fungal mycelial network structure.

The findings obtained regarding the tensile strengths of mycelium-based insulation boards perpendicular to the surface are given in Table 5. Tensile strength perpendicular to the surface shown by the internal bond test was considerably higher for mycelium-based insulation boards produced with GL fungus compared with those produced with PO fungus. The type of fungus used was highly effective on the tensile strength perpendicular to the surface of the mycelium-based insulation boards produced. The tensile strength values of mycelium-based insulation boards produced using GL fungus increased with increasing incubation time. This was thought to be attributable to the fact that the mycelium and network structure of the GL fungus is quite dense, and the boards are more rigid.



Error bars showing standard deviation

Fig. 3. Effect of fungal types and incubation time of mechanical properties on mycelium-based insulation boards

Table 5 and Fig. 3 present the results regarding the CS values of mycelium-based insulation boards at 10% deformation. The CS values of the boards produced using GL fungus were higher than those produced using PO fungus. The CS values of mycelium-based insulation boards decreased with increasing incubation time. The decrease in the CS values can be explained by the further destruction/degradation caused by fungi in the main chemical components of wheat straw with increasing incubation time. The decrease in CS values was significant. Considering that the mycelium-based insulation boards produced using GL fungus were more rigid/harder than those produced using the PO fungus, the CS values of mycelium-based insulation boards produced using GL fungus were higher.

Tacer-Caba *et al*. (2020) investigated the CS of mycelium-based composites produced from oat straw incubated with *Trichoderma asperellum*, *Agaricus bisporus*, PO, and GL fungi for 14 days. The compressive strength of mycelium-based composites varied between 16.8 and 299.6 kPa. Gan *et al*. (2022) produced mycelium-based composites from bamboo fibers inoculated with oyster mushrooms and incubated for 28 days without pressing. The compressive strength of the obtained mycelium-based composites increased as the fungal incubation time increased and was determined as 300 kPa at the end of the 28-day incubation period. The authors reported that the increase in compressive strength values as the fungal incubation time increased was attributable to the density of the fungal hyphae network structure. Ghazvinian *et al*. (2019) reported that the compressive strength of mycelium-based composites produced using PO fungus and wheat straw was 72.2 kPa.

In the present study, the compressive strength values of mycelium-based insulation materials produced using desilicated wheat straw were higher than those of the boards produced from non-desilicated wheat straw. High compressive strength values are thought to be due to factors such as better development of fungal mycelium, better binding between fungal mycelia and wheat straw, and density of fungal mycelium networks in pretreated wheat straws.

In general, some of the physical and mechanical properties of the mycelium composites produced from wheat straw without the desilication process determined by other researchers and from the desilicated wheat straw determined in this study were given in Table 7.

Table 7. Some Physical and Mechanical Properties of the Mycelium-based Composites Produced Either from Wheat Straw without the Desilication Process Determined by Other Researchers or from Desilicated Wheat Straw in this Study

Property	Substrate	Fungi	Mycelium composite	Values in this Study	Reference
Density (g/cm^3)	Crop residues (*Triticum sp.*)[1]; Straw[2, 3, 4]	*Pleurotus sp.*[1]; *Oxyporus Latermarginatus*[2]; *Megasporoporia minör*[2]; *Ganoderma Resinaceum*[2]; *Pleurotus ostreatus*[3]; *Trametes multicolor*[4]	0.183[1]; 0.277[3]; 0.094[4]; 0.051-0.061[2]	0.13-0.141	[1] López Nava *et al.* 2016; [2] Xing *et al.* 2018 [3] Ghazvinian *et al.* 2019; [4] Elsacker *et al.* 2019.
Water absorption (%)	Crop residues (*Triticum sp.*)[1]	*Pleurotus sp.*[1];	114.1-278.9[1];	135-250	[1] López Nava *et al.* 2016
MOR (kPa)	Crop residues (*Triticum sp.*)[1];	*Pleurotus sp.*[1];	10.91[1]	35-138	[1] López Nava *et al.* 2016
Compressive strength (kPa)	Crop residues (*Triticum sp.*)[1]; Straw[3]; Wheat straw[6]	*Pleurotus sp.*[1]; *Pleurotus ostreatus*[3]; *Ganoderma lucidum*[6]	41.72[1]; 20[3]; 70[6]	300-650	[1] López Nava *et al.* 2016; [3]Ghazvinian *et al.* 2019; [6] Răut *et al.* 2021

As can be seen in Table 7, the densities of the mycelium composites studied by other researchers ranged from 0.051 to 0.277, while the density in this current study ranged from 0.130 to 141 g/cm^3. The water absorption percentages in this study were found to be similar to other studies. It can be concluded that the desilication process did not increase or decrease the water absorption percentages. It was found that the MOR and compressive strength of the mycelium-based boards produced from desilicated wheat straw in this study were higher than the mycelium-based composites produced from wheat straw without the desilication process by other researchers (López Nava *et al.* 2016; Ghazvinian *et al.* 2019: Răut *et al.* 2021). It can be concluded that the desilication of the wheat straw enhanced some of the strength values of the mycelium-based composites.

CONCLUSIONS

The physical and mechanical properties of mycelium-based insulation boards produced from desilicated wheat straws were investigated in the present study. The results obtained were as follows:

1. The desilication pretreatment process resulted in the removal of roughly 35% of the silica content present in wheat straws.
2. The implementation of desilication pretreatment on wheat straws yielded enhanced mycelium growth. It resulted in a more compact structure, as well as improved bonding between the wheat straw and mycelium. Consequently, the mycelium-based insulation boards prepared in this study exhibited better mechanical characteristics.
3. The research revealed that the water absorption (WA) values of mycelium-based insulation materials prepared using desilicated wheat straw were considerably high. Nevertheless, the observed WA rates were comparatively lower than those reported by other researchers for mycelium-based composites.
4. Mycelium-based insulation boards produced in this study had high WA values, but the levels of thickness swelling (TS) were constrained.
5. Mycelium-based insulation boards produced with *Ganoderma lucidum* (GL) fungus demonstrated higher modulus of rupture (MOR) and modulus of elasticity (MOE) values than those made with *Pleurotus ostreatus* (PO) fungus for all three incubation periods.

ACKNOWLEDGMENTS

This research was funded by The Scientific and Technological Research Council of Turkey, grant number 118O145. The authors would like to thank Enago – https://www.enago.com.tr/ceviri/ for their assistance in manuscript translation and editing. The authors would also like to thank Rita Rentmeester for the fungi cultures (Northern Research Station United States Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA).

REFERENCES CITED

Abhijith, R., Ashok, A., and Rejeesh, C. R. (2018). "Sustainable packaging applications from mycelium to substitute polystyrene: a review," *Materials Today: Proceedings* 5(1), 2139-2145. DOI: 10.1016/j.matpr.2017.09.211

Appels, F. V., Camere, S., Montalti, M., Karana, E., Jansen, K. M., Dijksterhuis, J., and Wösten, H. A. (2019). "Fabrication factors influencing mechanical, moisture-and water-related properties of mycelium-based composites," *Materials and Design* 161, 64-71. DOI: 10.1016/j.matdes.2018.11.027

Arifin, Y. H., and Yusuf, Y. (2013). "Mycelium fibers as new resource for environmental sustainability," *Procedia Engineering* 53, 504-508. DOI: 10.1016/j.proeng.2013.02.065

ASTM C165 – 07 (2012). "Standard test method for measuring compressive properties of thermal insulations," ASTM International, West Conshohocken, PA, USA.
ASTM C203-05a (2012). "Standard test methods for breaking load and flexural properties of block-type thermal insulation," ASTM International, West Conshohocken, PA, USA.
ASTM C303–02 (2012). "Standard test method for dimensions and density of preformed block and board-type thermal insulation," ASTM International, West Conshohocken, PA, USA.
ASTM C578–04. (2004). "Standard specification for rigid, cellular polystyrene thermal Insulation," ASTM International, West Conshohocken, PA, USA.
ASTM D1037 (2012). "Standard test methods for evaluating properties of wood-based fiber and particle panel materials," ASTM International, West Conshohocken, PA, USA.
Bhuvaneshwari, S., Hiroshan Hettiarachchi, and Jay N. Meegoda. (2019). "Crop residue burning in India: Policy challenges and potential solutions," *International Journal of Environmental Research and Public Health* 16(5), article 832. DOI: 10.3390/ijerph16050832
Blackwell, M. (2011). "The Fungi: 1, 2, 3… 5.1 million species?," *American Journal of Botany* 98(3), 426-438. DOI: 10.3732/ajb.1000298
Bruscato, C., Malvessi, E., Brandalise, R. N., and Camassola, M. (2019). "High performance of macrofungi in the production of mycelium-based biofoams using sawdust—Sustainable technology for waste reduction," *Journal of Cleaner Production* 234, 225-232. DOI: 10.1016/j.jclepro.2019.06.150
Deniz, I. (1994). *Predesilication of Wheat (Triticum aestivum L.) Straw and the Action of this Pretreatment on O_2-NaOH Pulping Conditions*, Ph. D. Thesis, Karadeniz Technical University, Trabzon, Türkiye.
De Paula, R. G., Antoniêto, A. C. C., Ribeiro, L. F. C., Srivastava, N., O'Donovan, A., Mishra, P. K., Gupta, V. K., and Silva, R. N. (2019). "Engineered microbial host selection for value-added bioproducts from lignocellulose," *Microbial Engineering Biotechnologies* 37(6), article ID 107347. DOI: 10.1016/j.biotechadv.2019.02.003
Elsacker, E., Vandelook, S., Brancart, J., Peeters, E., and De Laet, L. (2019). "Mechanical, physical and chemical characterisation of mycelium-based composites with different types of lignocellulosic substrates," *PLoS One* 14(7), article ID e0213954. DOI: 10.1371/journal.pone.0213954
Elsacker, E., De Laet, L., and Peeters, E. (2022). "Functional grading of mycelium materials with inorganic particles: The effect of nanoclay on the biological, chemical and mechanical properties," *Biomimetics* 2022, 7, 57. DOI: 10.3390/biomimetics7020057
EN 319 (1999). "Particleboards and fiberboards. Determination of tensile strength perpendicular to the plane of the board," European Standards, Brussels, Belgium.
Eriksson, K. E. L., Blanchette, R. A., and Ander, P. (1990). "Morphological aspects of wood degradation by fungi and bacteria," in: *Microbial and Enzymatic Degradation of Wood and Wood Components*, Springer Series in Wood Science, Springer, Berlin, Heidelberg, Germany. DOI: 10.1007/978-3-642-46687-8_1
Ghazvinian, A., Farrokhsiar, P., Vieira, F., Pecchia, J., and Gursoy, B. (2019). "Mycelium-based bio-composites for architecture: Assessing the effects of cultivation factors on compressive strength," in: *Architecture in the Age of the 4th Industrial Revolution*, J. P. Sousa, G. C. Henriques, and J. P. Xavier (Eds.), Education and

Research in Computer Aided Architectural Design in Europe, Porto, Portugal, pp. 505-514. DOI: 10.5151/proceedings-ecaadesigradi2019_465

Gan, J. K., Soh, E., Saeidi, N., Javadian, A., Hebel, D. E., and Le Ferrand, H. (2022). "Temporal characterization of biocycles of mycelium-bound composites made from bamboo and *Pleurotus ostreatus* for indoor usage," *Scientific Reports* 12(1), 1-12. DOI: 10.1038/s41598-022-24070-3

Haneef, M., Ceseracciu, L., Canale, C., Bayer, I. S., Heredia-Guerrero, J. A., and Athanassiou, A. (2017). "Advanced materials from fungal mycelium: Fabrication and tuning of physical properties," *Scientific Reports* 7(1), 1-11. DOI: 10.1038/srep41292

Hawksworth, D. L. (2001). "The magnitude of fungal diversity: The 1.5 million species estimate revisited," *Mycological Research* 105(12), 1422-1432. DOI: 10.1017/S0953756201004725

Holt, G. A., Mcintyre, G., Flagg, D., Bayer, E., Wanjura, J. D., and Pelletier, M. G. (2012) "Fungal mycelium and cotton plant materials in the manufacture of biodegradable molded packaging material: Evaluation study of select blends of cotton byproducts," *Journal of Biobased Materials and Bioenergy* 6 (4), 431-439. DOI: 10.1166/jbmb.2012.1241

Hurter, A. M. (1988). "Utilization of annual plants and agricultural residues for the production of pulp and paper," Proceeding TAPPI Pulping Conference, TAPPI PRESS, New Orleans, p.139.

Jones, M., Huynh, T., Dekiwadia, C., Daver, F., and John, S. (2017). "Mycelium composites: A review of engineering characteristics and growth kinetics," *Journal of Bionanoscience* 11(4), 241-257. DOI: 10.1166/jbns.1440

Jones, M., Weiland, K., Kujundzic, M., Theiner, J., Kählig, H., Kontturi, E., John, S., Bismarck, A., and Mautner, A. (2019a). "Waste-derived low-cost mycelium nanopapers with tunable mechanical and surface properties," *Biomacromolecules* 20(9), 3513–3523. DOI: 10.1021/acs.biomac.9b00791

Jones, M. P., Lawrie, A. C., Huynh, T. T., Morrison, P. D., Mautner, A., Bismarck, A. and John, S. (2019b). "Agricultural by-product suitability for the production of chitinous composites and nanofibers utilising *Trametes versicolor* and *Polyporus brumalis* mycelial growth," *Process Biochemistry* 80, 95-102. DOI: 10.1016/j.procbio.2019.01.018

Kuştaş, S. (2022). *Production of Biodegradable Materials from Lignocellulosic Materials Incubated with Different White Rot Fungi and Determination of their Technological Properties*, Ph.D. Dissertation, Institute of Science and Technology, Karadeniz Technical University, Turkey. https://tez.yok.gov.tr/UlusalTezMerkezi/TezGoster?key=RsTBl6RWK25OBMIKtIgYYQbM_QQM2LcO4vymK1SFp8w3uj9h_fCu8UmsDfA3V-Jr

Li, M. M., Pan, H.C., Huang, S. L., and Scholz, M. (2013). "Controlled experimental study on removing diesel oil spillages using agricultural waste products," *Chemical Engineering Technology* 36(4), 673-680. DOI: 10.1002/ceat.201200658

López Nava, J. A., Méndez González, J., Ruelas Chacón, X., and Nájera Luna, J. A. (2016). "Assessment of edible fungi and films bio-based material simulating expanded polystyrene," *Materials and Manufacturing Processes* 31(8), 1085-1090. DOI: 10.1080/10426914.2015.1070420

Madurwar, M. V., Ralegaonkar, R. V., and Mandavgane, S. A. (2013). "Application of agro-waste for sustainable construction materials: A review," *Construction and Building Materials* 38, 872-878. DOI: 10.1016/j.conbuildmat.2012.09.011

Narayanaswamy, N., Dheeran, P., Verma, S., and Kumar, S. (2013). "Biological pretreatment of lignocellulosic biomass for enzymatic saccharification," in: *Pretreatment Techniques for Biofuels and Biorefineries. Green Energy and Technology*, Z. Fang (Ed.), Springer, Berlin, Heidelberg, pp. 3-34. DOI: 10.1007/978-3-642-32735-3_1

Nasreen, Z., Ali, S., Usman, S., Nazir, S., and Yasmeen, A. (2016). "Comparative study on the growth and yield of Pleurotus ostreatus mushroom on lignocellulosic by-products," *International Journal of Advanced Research in Botany.* 2(1), 42-49. DOI: 10.20431/2455-4316.0201006

Pelletier, M. G., Holt, G. A., Wanjura, J. D., Bayer, E., and McIntyre, G. (2013). "An evaluation study of mycelium based acoustic absorbers grown on agricultural by-product substrates," *Industrial Crops and Products* 51, 480-485. DOI: 10.1016/j.indcrop.2013.09.008

Răut, I., Călin, M., Vuluga, Z., Oancea, F., Paceagiu, J., Radu, N., Doni, M., Alexandrescu, E., Purcar, V., Gurban, A.-M., *et al.* (2021). "Fungal based biopolymer composites for construction materials," *Materials* 14(11), article 2906. DOI: 10.3390/ma14112906

Sauerwein, M., Karana, E., and Rognoli, V. (2017). "Revived beauty: Research into aesthetic appreciation of materials to valorise materials from waste," *Sustainability* 9(4), article 529. DOI: 10.3390/su9040529

Sun, W., Tajvidi, M., Hunt, C. G., McIntyre, G., and Gardner, D. J. (2019). "Fully bio-based hybrid composites made of wood, fungal mycelium and cellulose nanofibrils," *Scientific Reports* 9(1), article 3766. DOI: 10.1038/s41598-019-40442-8

Tacer-Caba, Z., Varis, J. J., Lankinen, P., and Mikkonen, K. S. (2020). "Comparison of novel fungal mycelia strains and sustainable growth substrates to produce humidity-resistant biocomposites," *Materials & Design* 192, article ID 108728. DOI: 10.1016/j.matdes.2020.108728

Tedersoo, L., Bahram, M., Põlme, S., Kõljalg, U., Yorou, N. S., Wijesundera, R., Ruiz, L. V., Vasco-Palacios, A. M., Thu, P. Q., Suija, A., *et al.* (2014). "Global diversity and geography of soil fungi," *Science* 346(6213), article ID 1256688. DOI: 10.1126/science.1256688

Tutus, A., and Eroglu, H. (2004). "An alternative solution to the silica problem in wheat straw pulping," *Appita: Technology, Innovation, Manufacturing, Environment*, 57(3), 214-217. DOI: 10.3316/informit.720368708560774

Webster, J., and Weber, R. (2007). *Introduction to Fungi*, Cambridge University Press, Cambridge, UK. DOI: 10.1017/CBO9780511809026

Wei, L., Liang, S., and McDonald, A. G. (2015). "Thermophysical properties and biodegradation behavior of green composites made from polyhydroxybutyrate and potato peel waste fermentation residue," *Industrial Crops and Products* 69, 91-103. DOI: 10.1016/j.indcrop.2015.02.011

Wesenberg, D., Kyriakides, I., and Agathos, S. N. (2003). "White-rot fungi and their enzymes for the treatment of industrial dye effluents," *Biotechnology Advances* 22(1-2), 161-187. DOI: 10.1016/j.biotechadv.2003.08.011

Xing, Y., Brewer, M., El-Gharabawy, H., Griffith, G., and Jones, P. (2018). "Growing and testing mycelium bricks as building insulation materials," in: *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, Vol. 121, p. 022032.

Yildirim, N. (2018). "Performance comparison of bio-based thermal insulation foam board with petroleum-based foam boards on the market," *BioResources* 13(2), 3395-3403. DOI: 10.15376/biores.13.2.3395-3403

Zabihzadeh, S. M. (2010). "Water uptake and flexural properties of natural filler/HDPE composites," *BioResources* 5(1), 316-323. DOI: 10.15376/biores.5.1.316-323

Article submitted: November 4, 2023; Peer review completed: December 2, 2023; Revised version received: December 23, 2023; Accepted: January 1, 2024; Published: January 8, 2024.
DOI: 10.15376/biores.19.1.1330-1347