Research article

Sustainability Initiatives in the Wood Processing Industry: Utilizing Sawdust in the Production of Mycelium-Based Biocomposites to Develop Circular Materials

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Abstract The wood processing industry plays a pivotal role in the global economy and the environment and its preservation. Sustainability continues to gain worldwide importance, and wood processing industries are actively seeking innovative solutions to minimize waste and environmental impact. One promising approach utilizes sawdust, a byproduct of wood processing, as a substrate to produce mycelium-based biocomposites (MBCs) to create circular materials. This research explored the feasibility of utilizing sawdust derived from three different wood types, red alder, white oak, and yellow poplar, to produce MBCs. The process used fungal mycelium from the genus *Ganoderma* sp. (WE-CMU 011) as a biopolymer to bind the sawdust particles together. The mechanical and physical properties of the obtained MBCs were then examined and compared with traditional synthetic materials. The results include that the obtained MBCs exhibited density levels and compression strengths ranging from 167.71 to 208.28 kg/m^3 and 387.28 to 562.06 kPa, respectively, surpassing those of many synthetic foams. Particularly, MBCs produced from a combination of mixed sawdust and white oak sawdust demonstrated superior compression strength and density compared to MBCs made from other wood types. Additionally, using a blend of sawdust from all three wood types during production resulted in MBCs with lower average shrinkage and volumetric swelling. The obtained MBCs demonstrated water absorption of 110.99% to 139.37%, which is higher than synthetic materials. The water-absorbing capacity of MBCs, however, may find application in agriculture for retaining moisture, in packaging materials for liquid chemicals prone to leaks during transportation, and in some housewares. Importantly, this study provides valuable insights into the wood processing industry and environmental advocates and highlights the potential of circular material production for achieving sustainable, eco-friendly, and economically viable practices.

Keywords agro-industrial waste, green composite materials, mycelium technology, build a Biobased economy, BCG model

INTRODUCTION

The wood processing industry stands as a cornerstone of the global economy and international trade, yet the imperative of environmental preservation has prompted a reevaluation of its practices (Sujová et al., 2015). Currently, industry faces significant environmental challenges, primarily stemming from the generation of waste. Sawdust, a byproduct of wood processing, is one such waste material that poses challenges for disposal and environmental management. Sawdust has typically been disposed of in landfills or through incineration and is sometimes used for low-value applications such as in cultivation materials, mulching, fuel, or animal bedding. However, these disposal methods are not sustainable in the long term and can have adverse environmental impacts, including soil and water contamination, greenhouse gas emissions, and habitat destruction (Kura, 2020). In response to the growing importance of sustainability, the wood processing industry is actively seeking innovative solutions to mitigate waste and minimize its environmental footprint (Adhikari and Ozarska, 2018). A promising approach within this paradigm shift involves harnessing the untapped potential of sawdust, a byproduct of wood processing, to create MBCs (Yang and Qin, 2023).

This potentially groundbreaking research endeavors to explore the feasibility of incorporating sawdust from diverse wood types into the manufacturing of MBCs. The methodology involves the utilization of fungal mycelium from mushroom of the genus *Ganoderma*, known for its edible and medicinal properties (Butu et al., 2020), as a biopolymer to bind substrate particles together during the MBC formation process. The study meticulously examined the mechanical and physical properties of the resultant MBCs, drawing comparisons with traditional synthetic materials. The primary goal was to evaluate MBCs as a potential substitute material for synthetic foams, particularly for packaging materials and in the production of various household items. Notably, the obtained outcomes of this research provide useful future approaches and viewpoints in the context of the bio-circular-green economy (BCG model) within the wood processing industry.

Beyond offering valuable insights into the wood processing industry and concerned environmentalists, this study may highlight the groundbreaking possibilities of circular material production. Overall, the exploration of utilizing sawdust in the production of MBCs exemplifies the concept and potential of the BCG model to drive sustainable development within the wood processing industry. By examining and potentially embracing principles of resource efficiency, ecological balance, and biotechnological innovation, stakeholders can pave the way for a more sustainable future, where waste is minimized, resources are maximized, and environmental impacts are mitigated.

OBJECTIVES

The aims of this research are 1) to explore the utilization of sawdust as a substrate for fungal mycelium from the *Ganoderma* sp. (WE-CMU 011) and used as a biopolymer to produce MBCs for the creation of circular materials, 2) to investigate the mechanical and physical properties of the obtained MBCs with comparison to traditional synthetic materials, and 3) define the potential uses of MBCs and the potential of circular material production for achieving sustainable, eco-friendly, and economically viable practices.

METHODOLOGY

Sawdust and Mushroom Mycelium Source

In this experiment, three types of wood sawdust, red alder (RA), white oak (WO), and yellow poplar (YP), and a sawdust mixture (MX) containing an equal ratio (1:1:1) of the three sawdust types, were utilized as primary substrates. The sawdust from each wood type was obtained from Modern Frame Co., Ltd., a wood processing factory in Bangkok, Thailand. Before experimentation, all sawdust was fully dried in an oven at 60°C. The mushroom mycelium of *Ganoderma* sp. WE-CMU 011 was selected for the study as this genus has been studied previously and reported to produce MBCs with several advantageous properties (Aiduang et al., 2022a). The mushroom mycelium was sourced from the Sustainable Development of Biological Resources Laboratory (SDBR-CMU), Faculty of Science, Chiang Mai University, Thailand. Before experimentation, the pure mycelium was cultivated on potato dextrose agar (PDA; Conda, Madrid, Spain) and incubated at 30°C for 7 days.

Substrate Preparation and MBCs Production

Sawdust, along with supplement substrates (5% rice bran, 1% calcium carbonate, 2% calcium sulfate, and 0.2% sodium sulfate) on a dry mass basis, were mixed. The mixture (800 g) was placed in culture bags, sealed with cotton-plugged PVC pipe rings, and autoclaved at 121°C for 60 min. After cooling for 24 hours., 5 g of fully mycelium-colonized sorghum inoculum was transferred to each bag. Bags were then incubated at 30°C in darkness for 30 days or until full colonization occurred.

The colonized sawdust was finely ground, filled into a purpose-designed mold, and then subjected to incubation at 30°C for five days. After the five-day incubation, MBCs were removed, incubated for an additional three days for full mycelial coverage, and then dried at 70°C for 24 to 48 hrs until stabilized. The dried MBCs were weighed, measured for size, and subsequently stored in desiccators for further investigation (Aiduang et al., 2022b).

Determination of Physical Properties

The density of the obtained MBCs was calculated using the ISO 9427 standard, considering both mass and volume. The shrinkage rate was determined by calculating the percentage shrinkage (%), expressed as $(V_1-V_2/V_1) \times 100$, where V_1 is the wet volume and V_2 is the dry volume of the sample, following the method outlined by Elsacker et al. (2019). Ten replications were completed to ensure accurate data.

The water absorption and volumetric swelling of the obtained MBCs were assessed following the ASTM C272/C272M-18 standards. After drying the MBC samples until stable mass, the initial weight was measured, and the samples were then cooled in a desiccator for 24 hours MBC samples were then immersed in deionized water for 24 hours, with weight measurements taken at specific intervals (2nd, 4th, 6th, 12th, 16th, and 24th hours). Weight increase (%) was calculated as $[(W-D)/D] \times 100$ (where W is wet weight, and D is dry weight) (Aiduang et al., 2022b). Volumetric swelling after 24 hours was determined by comparing volume changes to the initial volume (Zimele et al., 2020).

Determination of Mechanical Property

The compression strength of the obtained MBCs was measured using ASTM C 165-07 standards. Strength, defined as stress at 20% deformation, was tested using a Hounsfield-H10Ks universal testing machine (New York, NY, USA) at a controlled displacement rate of 5 mm/min. Compression strength was calculated following the formula described by Vidholdová et al. (2019).

Statistical Analysis

Data from each experiment underwent analysis using one-way analysis of variance (ANOVA) in SPSS version 16.0 for Windows. Significant differences ($p \leq 0.05$) between mean values were identified using Duncan's multiple range test.

RESULTS AND DISCUSSION

Density Levels and Shrinkage Percentages of MBCs

Table 1 demonstrates the density values of the obtained MBCs, which varied from 167.72 to 208.28 kg/m^3 depending on the type of sawdust substrate used. As illustrated in Fig. 1, the WO sawdust MBCs exhibited the greatest density at 208.28 kg/m^3, followed by the 1:1:1 mixture of all three sawdust types at 187.29 kg/m^3. However, there was no statistically significant difference between these two densities. Conversely, MBCs derived from YP sawdust showed the lowest density level at approximately 167.72 kg/m^3, with no statistically significant difference compared to MBCs produced from RA sawdust, which averaged 179.42 kg/m^3. These density variations align with several previous studies, indicating that the density of MBCs is generally affected by various factors related to substrate type, substrate particle size, substrate composition, the density of individual materials, volume fraction, porosity, mycelium strain, growth conditions, and growth time, along with post-processing techniques (Appels et al., 2019; Aiduang et al., 2022a; Alemu et al., 2022; Houette et al., 2022; Sydor et al., 2022). In this study, the differing density of MBCs may be influenced by the substrate type used in the experiment, as each sawdust variant possesses distinct particle sizes, characteristics, and densities of individual materials. Furthermore, the varying composition of the substrate directly affects mycelium growth and colonization performance, thereby impacting the density of MBC materials. However, the obtained density levels of MBCs in this study are consistent with those from previous studies, falling within the range of 25-954 kg/m^3 (Aiduang et al., 2022a). Importantly, these density values are comparable to many synthetic foams (11-920 kg/m^3), suggesting MBCs as promising materials for various industries, particularly in packaging applications and various household items, where Expanded Polystyrene Foam (EPS) and Polyurethane (PU) foams are commonly utilized (Jones et al., 2020; Aiduang et al., 2022b).

Table 1 Density and average shrinkage of MBCs by sawdust type

Sawdust type	Density (kg/m^3)	Shrinkage (%)
MBCs produced from RA sawdust	179.42±6.04^{b}	8.29±0.45^{ab}
MBCs produced from WO sawdust	208.28±7.93^{a}	9.11±1.03^{a}
MBCs produced from YP sawdust	167.72±11.33^{b}	7.59±0.43^{ab}
MBCs produced from MX sawdust	187.29±6.93^{ab}	6.81±0.67^{b}

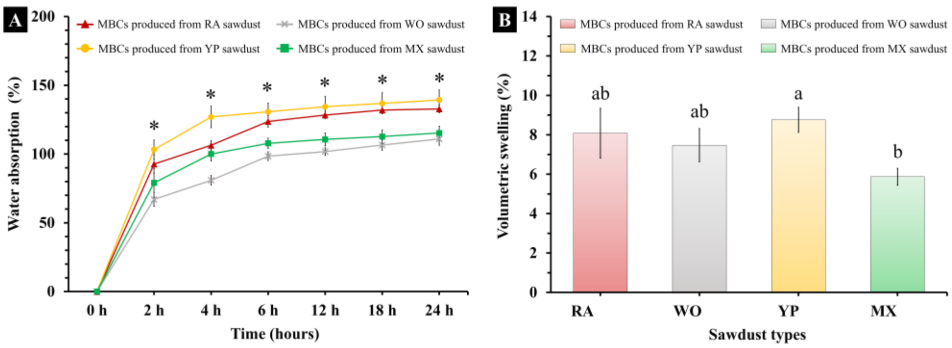
The results mean ± standard deviation. Different letters in the same column are considered significantly different according to Duncan's multiple range test (p ≤ 0.05).

Fig. 1 MBC samples from each type of sawdust utilized during the study

Table 1 also demonstrates the average shrinkage of MBCs which ranged from 6.81% to 9.11% depending on the type of sawdust substrate used. The MBCs created by MX sawdust exhibited the least shrinkage, followed by those produced from YP (7.59%) and RA sawdust (8.29%). In contrast, MBCs derived from WO sawdust displayed the greatest shrinkage at approximately 9.11%. The observed variations in MBC shrinkage in this study align with findings from several previous studies, indicating that the average shrinkage of MBCs is commonly influenced by various factors, including substrate type, mycelium species in manufacturing, moisture content in material samples, and the specific drying method and temperature selected (Elsacker et al., 2019; Aiduang et al., 2022b). In this study, the utilization of different sawdust types in the production process may impact on the internal structure system, material volumetrics, and the occurrence of moisture levels within the composite. These factors could contribute to varying shrinkage rates of MBCs. Nevertheless, the average shrinkage of MBCs produced from each sawdust type in this study aligns with findings from previous research, falling within the range of 6.2% to 15.0% (Aiduang et al., 2022b). This consistent performance indicates a positive trend, making these MBCs a promising choice for future manufacturing materials across a diverse range of applications, particularly in materials requiring consistent dimensional stability, such as specific packaging materials and semi-construction materials that do not need to bear significant loads, like non-load-bearing infill walls.

Water Absorption and Volumetric Swelling Levels

The water absorption results are shown in Fig. 2 (A). MBCs produced by YP sawdust had the highest water absorption rate, reaching 139.37% in 24 hours. In contrast, those produced from WO sawdust showed the lowest absorption rate at 110.00% after 24 hours. Likewise, MBCs from RA and MX sawdust demonstrated absorption rates of 132.82% and 115.29%, respectively, after 24 hours. Most of the water absorption occurred within the initial 2 to 6 hours, with the water absorption rate slowing thereafter. The water absorption behaviors observed in this study align with those reported in earlier studies on MBC materials. Water absorption capacities of MBCs are defined by a variety of factors, including the density of composites, chemical components associated with cellulose content, the level of fungal hydrophobic coating on the material surface, and the particle size of substrates used (Appels et al., 2019; Jones et al., 2020). Typically, MBCs with high density and a substantial coating of hydrophobic mycelium tend to exhibit reduced water absorption (Appels et al., 2019). Conversely, MBCs with a high cellulose component show increased water absorption because they contain a larger number of accessible hydroxyl groups. Furthermore, using smaller particle-sized substrates in production can reduce the water absorption capacities of MBCs, as they often exhibit high density. Despite these considerations, the water absorption capacities of MBC materials remain greater compared to traditional synthetic materials. The study suggests that innovation and improvements in this property might unlock more functionalities for MBCs. However, the MBCs obtained in this study fall within the range reported in previous research, where water absorption levels for MBCs ranged from 24.45% to 560% when submerged in water over 24 to 192 hours (Aiduang et al., 2022a). This characteristic could be advantageous in specific applications, especially in fields such as absorbent pad materials, agricultural products, and packaging materials that require the absorption of liquids in the event of a spill.



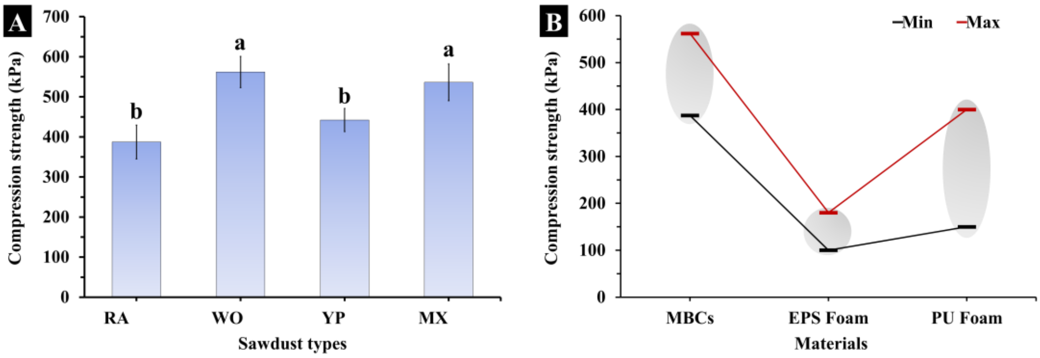
Mean values with error bars (± standard deviation) are shown. "" denotes significant differences by Duncan's multiple range test ($p \leq 0.05$). Different letters within the same experiment indicate significant differences ($p \leq 0.05$).*

Fig. 2 The water absorption abilities and volumetric swelling levels of the MBCs obtained in this study

Volumetric swelling serves as a key indicator for the stable dimensional performance of composite materials, as illustrated in Fig. 2 (B). Most of the water absorption rates align with the volumetric swelling levels since it causes a change in volume and dimensions. MBCs made from YP had the greatest volumetric swelling level at 8.76%, whereas MBCs made from mixed types of sawdust had the least volumetric swelling at 5.87%. These findings highlight the direct influence of water absorption levels on the primary volumetric swelling of MBCs, which follows the established theories. The low volumetric swelling observed in MBCs was attributed to their low water uptake behavior, which was associated with the high density of composites and an effective mycelium coating on the material surface (Appels et al., 2019; Zimele et al., 2020). This coating functions as a resistance to slowing the absorption into the material when the surface comes into contact with water (Appels et al., 2019). In addition, incorporating substrate during the manufacturing process may help to improve the internal structure system and material density, potentially contributing to the enhanced dimensional stability of the material (Nasr et al., 2023). However, the volumetric swelling of the MBCs obtained in this study was comparable to those created in several previous studies (0.3-21.0%) (de Lima et al., 2020; Zimele et al., 2020) and remained within the range of some types of paper-based and wood-based products (5-12% and 1.9-25%, respectively) (Teeraphantuvat et al., 2024). This suggests that MBCs have the potential to become a new generation of alternative materials in various fields, such as cushioning packaging materials, household items, or semi-construction products, replacing traditional synthetic materials.

Compression Strength

Figure 3(A) indicates the compression strength values of the MBCs obtained. The study revealed variations in the compression strength of MBCs based on the different substrates used. Specifically, the use of WO sawdust and MX sawdust in MBC production resulted in MBCs with high compression strength, measuring 562.06 kPa and 536.28 kPa, respectively. Conversely, the utilization of YP and RA led to MBCs with compression strength of 442.19 kPa and 387.28 kPa, respectively. These findings emphasize that the choice of substrate significantly influences the resulting compression strength of the MBCs. Several prior studies indicate that variations in the compression strength of MBCs are primarily attributed to diverse parameters employed in the fabrication processes. These parameters include the type of substrate, different fungal species, and pressing techniques utilized throughout production (Elsacker et al., 2019; Aiduang et al., 2022b; Vašatko et al., 2022). In terms of substrate type, compositional differences, material density, porosity, and particle size collectively influence the compression strength of MBCs. Similarly, fungal species, mycelium growth, conditions, and colonization time play significant roles in impacting the compression strength of MBCs (Vašatko et al., 2022; Alaneme et al., 2023). Furthermore, various research studies have pointed out that each pressing technique employed during production is a contributing factor to the varying compressive strength of MBCs (Aiduang et al., 2022b). However, this study reveals that the obtained MBCs exhibit similarities to and even surpass some traditional synthetic foams as shown in Fig. 3(B). Moreover, the compression strength falls within the range observed in MBCs from several earlier studies (30 to 4,400 kPa) (Elsacker et al., 2019; Jones et al. 2020; Aiduang et al., 2022a). This emphasizes the promising mechanical properties of MBC materials produced from factory sawdust, suggesting their potential use as replacements for traditional foams, especially products that are typically made from PU foams.



The compression strength of MBCs is produced from a combination of fungal mycelium with sawdust of each wood (A). A comparison of MBCs compressive strength with synthetic foams (B). Different letters within the same experiment denote significant differences ($p \leq 0.05$).

Fig. 3 Compression strength of MBCs

CONCLUSION

This research investigated the properties of MBCs derived from the use of different sawdust substrates. Density varied from 167.72 to 208.28 kg/m^3, with WO sawdust demonstrating the greatest density (208.28 kg/m^3), which was similar to the density observed in MX sawdust. Shrinkage percentages ranged from 6.81% to 9.11%, showing promising consistency across various sawdust types. Water absorption rates varied, with YP sawdust MBCs exhibiting the highest (139.37% in 24 hours) and WO sawdust MBCs the lowest (110.00% after 24 hours). Volumetric swelling levels correlated with water absorption, indicating stable dimensional performance. Compression strength varied based on the substrates used, with WO and MX sawdust MBCs surpassing some synthetic foams. Overall, the study highlights the promising mechanical and physical properties of MBCs, suggesting their potential as eco-friendly alternatives in diverse applications involving packaging, household goods, as well as in some elements in agriculture systems. Nevertheless, further exploration of this sector is required to fully define and unlock its potential. Suggestions include exploring combinations of diverse materials and employing different species of mushroom mycelium during production which might enhance properties and expand the range of applications.

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