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Influence of Drying Temperature in the Oven on Physical, Morphology and Mechanical Properties of Mycelium Composite

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ABSTRACT

Mycelium, a root-like fungi network, possesses distinctive characteristics that render it an appealing contender for replacing polystyrene (PS). Drying in the oven is one of the most commonly used methods for producing mycelium composites. However, achieving its desired properties requires proper control of the drying temperature. This research aims to develop a mycelium-based composite by utilising an edible mushroom, specifically *Pleurotus ostreatus* (oyster mushroom), as an alternative to non-biodegradable materials for packaging applications. The composite is developed by inoculating *Pleurotus ostreatus* fungi into the substrate, mainly consisting of kenaf, wheat bran and $CaCO_3$. Afterwards, the composite was incubated for 20 days and then subjected to drying at different oven temperatures (e.g. 40°C, 60°C, and 80°C) for 24 hours. Our findings indicate that the desirable mechanical properties of mycelium composite were found at 60°C, where flexural strength, flexural modulus and impact strength were obtained at 0.11 MPa, 4.15 GPa and 635.8 N, respectively. The moisture content was 26.13%, and the shrinkage was 20.73%. The obtained density of 0.15 g/cm^3 was compared to the density of PS, which is 1.04 g/cm^3. This research indicates that a lightweight composite material, consisting of a network of interconnected hyphae that function as a natural adhesive, holds significant potential as a viable solution for achieving a more sustainable and environmentally friendly future, primarily due to its biodegradability.

Keywords: Drying temperature, fungi, mechanical property, mycelium, *Pleurotus ostreatus*

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INTRODUCTION

The subterranean network of fungi, known as mycelium, has garnered attention as a

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potentially valuable bio-based material due to its widespread presence, ability to regenerate and minimal environmental impact. It has led to the development of mycelium-based composites, a type of bio-composite material formed by the interaction between mycelium, the vegetative part of a fungus and lignocellulosic substrate. These substrates, derived from plant matter (such as agricultural waste or wood chips), provide nutrients for the mycelium to grow and bind the material together. The resulting composites are lightweight and strong and exhibit excellent thermal and acoustic insulation properties, making them attractive for various applications, including packaging, textiles, construction and furniture (Brudny et al., 2024; Madusanka et al., 2024).

Mycelium composites offer a promising sustainable alternative to polystyrene (PS) derived from petroleum, a non-renewable resource. They exhibit distinctive characteristics, including low weight, biodegradability, and the capacity to be shaped into diverse forms (Sydor et al., 2021). The lightweight of mycelium composites can alleviate physical strain in handling, which is beneficial in applications where weight reduction is crucial. Unlike PS, which can linger in the environment for centuries, mycelium composites are naturally biodegradable. They can be broken down by microorganisms over time, returning to the earth without leaving harmful residues, thus reducing long-term waste and minimising their ecological footprint. Additionally, mycelium composites exhibit a remarkable ability to be moulded into various shapes during their growth phase. This property allows for creating custom-designated products with intricate geometries and tailored functionalities. Moreover, their non-toxic nature makes them suitable for use in a range of products, unlike PS, which can release harmful chemicals.

While mycelium composites can be engineered to exhibit good mechanical properties, they may not always match the strength and durability of PS, especially in applications requiring high load-bearing capacity. Apart from that, mycelium composites are naturally hygroscopic, meaning they have the ability to absorb moisture. It can affect their dimensional stability and mechanical properties, limiting their use in humid environments or applications requiring water resistance. Apart from that, the production of mycelium composites involves a longer biological growth phase (15-20 days) compared to the rapid production of PS. Despite their limitations, development efforts are crucial to improve the performance and applicability of mycelium composites, further establishing their position as a viable and environmentally friendly alternative to PS.

Various factors, including the choice of mycelium species and the type of lignocellulosic substrate, influence mycelium composites' properties. For example, *Ganoderma lucidum* is known for its rapid growth and dense hyphal network, while *Pleurotus ostreatus* is valued for its ability to degrade (Akromah et al., 2024). Process variables such as incubation time, temperature, humidity and pressure during the growth phase significantly affect the composite's final properties. Among these factors, drying temperature is particularly critical in determining the ultimate characteristics of mycelium composites. Various drying methods are accessible, each exerting unique impacts on the composite material, including air, freeze, supercritical, and oven drying. Air drying is a straightforward and economically efficient approach in which mycelium composites are allowed to undergo natural drying in the surrounding environment (Jones et al., 2020). However, it often leads to inconsistencies due to uncontrolled environmental conditions. The process of freeze-drying, scientifically referred to as lyophilisation, entails freezing mycelium composites followed by exposure to reduced pressure, resulting in the direct sublimation of frozen water from ice to vapour. This method preserves the microstructure but is more expensive and time-consuming. Supercritical drying employs a supercritical fluid, such as carbon dioxide (CO_2), to eliminate moisture from composites (Piskov et al., 2020). Although this method exploits the distinctive characteristics of supercritical fluids, which function as solvents and drying agents, it also increases complexity and cost. Mycelium composites are placed in a controlled temperature environment during oven drying, typically utilising convection furnaces. When comparing air and freeze-drying, using elevated temperatures in oven drying expedites the drying procedure. Although oven drying is a common method for removing moisture and offers better control over temperature, it can also lead to inconsistencies due to variations within the oven.

As mycelium grows, it forms a network of branching hyphae, primarily composed of chitin, that extend from the substrate into the air. It creates a fluffy skin covering the substrate and a vast three-dimensional matrix. Fungal growth in colonised substrates can be stopped through drying or heating. While frying induces a dormant state in the mycelium, allowing for potential regrowth under favourable conditions, heating deactivates the strains permanently, preventing further growth and detoxifying potentially harmful strains (Alemu et al., 2022). Managing the drying temperature within the mycelium composite presents a significant challenge in this situation. Inconsistencies in the properties of the dried composite may arise due to uneven moisture removal caused by variations in temperature and airflow within the oven. When subjecting mycelium composites to low-temperature drying, it is feasible to maintain the structural integrity and mitigate excessive shrinkage.

However, there exists a potential drawback of inadequate moisture elimination, leading to elevated moisture levels and reduced mechanical strength (Santos et al., 2021). Frying mycelium composites at elevated temperatures can accelerate drying by promoting rapid moisture removal. However, this method may also result in significant shrinkage, distortion and decreased porosity (Jones et al., 2018). In another study, Attias et al. (2020) developed a mycelium composite using three fungi species: *Colorius versicolor* (also known as *Trametes versicolor*), *Trametes ochracea* (the current scientific name for *Trametes multicolor*) and *Ganoderma sessile*. After incubation, the composites were oven-dried at 40°C for 72 hours, but as fungal growth was not yet fully terminated, an additional heat treatment of

100°C for 2 hours was conducted. Hence, expanding the investigated temperature range is crucial to fully comprehend the behaviour of mycelium composites, particularly in terms of terminating mycelium growth, rendering the material biologically inactive and achieving desired material properties (Islam et al., 2018).

Prior research may have focused on a restricted range of oven temperatures, omitting a comprehensive examination of the effects of temperature on mycelium composites. For example, Bagheriehnajjar et al. (2023) investigated using bamboo fibres as a renewable lignocellulosic substrate in mycelium composites, drying all samples at 70°C for 10 hours in an oven. Sakunwongwiriya et al. (2024) produced a mycelium composite from water hyacinth using four fungal species *(Pleurotus ostreatus, Pleurotus sajor-caju, Auricularia auricula-judae and Schizophyllum commune*). The samples were placed in an oven at 90°C until a constant weight was achieved, but the authors did not report the drying duration. Gaff et al. (2024) created a mycelium composite from *Ganoderma lucidum* spawn, employing a two-step drying process: initial air drying at room temperature for 2 days and oven drying at 120°C for 3 hours. Sim et al. (2017) examined the effects of vacuum and oven drying on the radical scavenging activity and nutritional content of *Maitake (Grifola frondosa)* mycelia. Their findings indicated that vacuum drying at 70°C and 1000 mBar was more effective in preserving these properties compared to direct oven drying at 105°C for 24 hours. Kim et al. (2016) investigated the drying characteristics of medicinal (*Ganoderma lucidum, Phellinus linteus*) and edible *(Pleurotus eryngii, Lentinus edodes)* mushrooms using a hot-air dryer at 50°C and 70°C. They found that the drying rate was highest at 70°C but concluded that 50°C was the most efficient drying method for both types of mushrooms. Mandliya et al. (2022) investigated the effects of vacuum drying at various temperatures (40°C–60°C) and pressures (60–260 mmHg) on the microstructure and physicochemical properties of pressed *Pleurotus eryngii* mycelium. They found that drying at 60°C and 60 mmHg resulted in the lowest water activity (0.215 ± 0.004) and browning index (28.946 ± 0.066) while maximising the water absorption index (5.365 ± 0.046 g/g).

Based on the literature review, the existing studies have focused on vacuum drying, which may not directly translate to the effects of oven drying due to differences in pressure and heat transfer mechanisms. They have often focused on limited temperature ranges and primarily investigated the influence of drying on nutritional content, drying rates, or specific physicochemical properties rather than the full range of properties relevant to mycelium composites. Additionally, there is no standardised drying method, as these processes' effectiveness depends on the specimens' dimensions. Hence, there remains a gap in the research regarding the influence of a wider range of oven temperatures on mycelium composite's physical, morphological and mechanical properties. Further research is needed to elucidate the microstructural changes occurring during drying and their correlation with observed mechanical properties. Hence, this research aims to address these gaps by fabricating mycelium composites using *Plerotus ostreatus* as spawn and kenaf as a substrate and systematically investigating the effects on a larger range of drying temperatures (e.g. 40°C, 60°C, and 80°C) in determining the composite's properties.

MATERIALS AND METHODS

Fabrication of Mycelium Composite

Figure 1 shows the step-by-step fabrication process of the mycelium composite, encompassing substrate preparation, inoculation and moulding, incubation, and finally, the drying process. The substrate was supplied by Fungitech Sdn Bhd, Pulau Pinang and was prepared in accordance with the formulation specified in Table 1. The substrate for the mycelium composite was formulated by combining 80% kenaf, 19% wheat bran and 1% $CaCO_3$. The liquid was spawned from *Pleurotus ostreatus* (oyster mushroom) and grown on the substrate. The substrate was sterilised at a temperature of 100°C to eliminate the possibility of contamination by bacteria, fungus, and other potential pathogens.

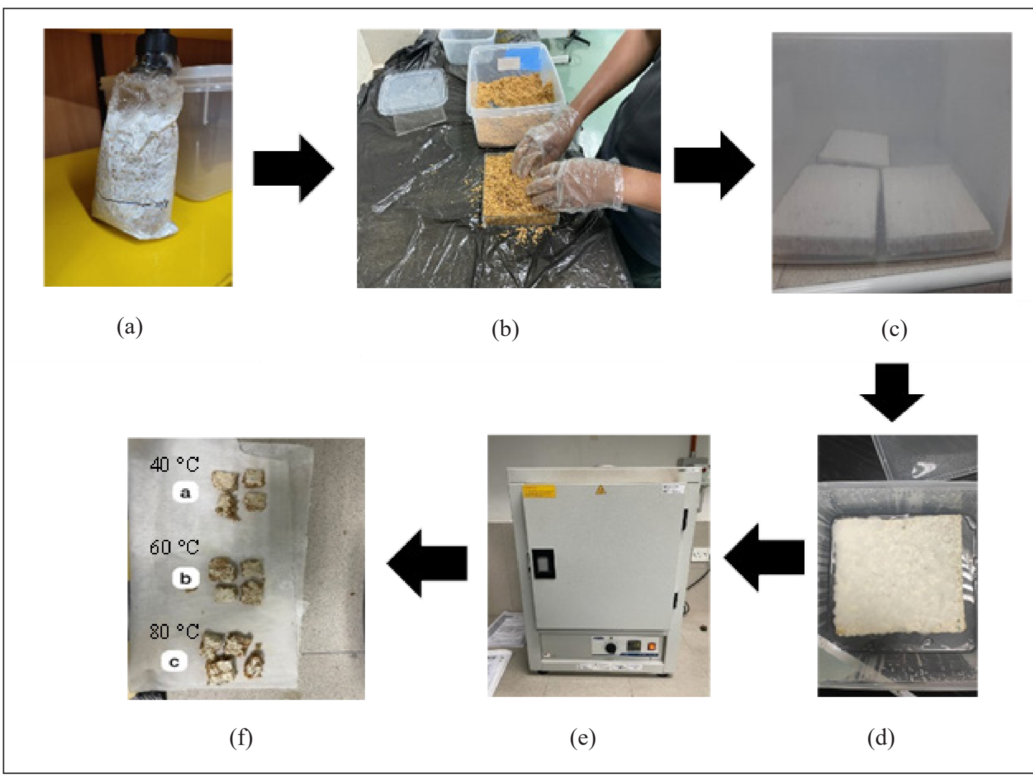

Figure 1. The fabrication process of mycelium composite: (a) Substrate collected, (b) Packing in acrylic mould, (c) Incubation, (d) Harvest mycelium composite, (e) Drying in the oven for 24 hours at 40°C, 60°C, 80°C, and (f) Characterisation of mycelium composite

Table 1
Formulation of mycelium composite

Materials	Kenaf	Wheat bran	$CaCO_3$
Percentage of weight mixture (%)	80	19	1

When the mycelium began to grow in the substrate, it was evenly distributed and compacted into the acrylic moulds measuring 155 × 155 × 10 mm (length x width x height). After filling the mould with the substrate, pressure was applied to the substrate to compact it further. This step promoted denser growth and improved adhesion between substrate particles, resulting in a stronger final product. Once the moulds were filled, they were placed in a container for incubation.

After filling and compacting the substrate within the moulds, they were placed in a closed container for incubation. The fungi thrive and produce mycelium optimally within a temperature range of 25°C–30°C and a humidity level of 60% – 65%. The incubation lasted for 20 days, during which the mycelium colonised the substrate, binding the particles together and forming a solid composite structure.

After incubation, the former mycelium composites were then subjected to a drying process using an oven (model: Protech GOV-50D). The drying process involved three different temperatures (e.g. 40°C, 60°C, and 80°C). Each composite was dried for 24 hours at its designated temperature. Following 24 hours of drying, the composites were removed from the oven and allowed to cool at room temperature. The dried composites were subsequently inspected for testing and characterisation.

Characterisation of Mycelium Composite

Density Measurement

Density evaluation was performed using an electronic densimeter (Biobase, model: BK-DME 3005). A sample measuring 10 × 10 mm was prepared for the test. The sample was carefully placed onto the densimeter, and the densimeter measured the mass and volume of the sample to determine its density. The density of the sample was determined by dividing the mass of the sample by its volume. The densimeter determined the sample's mass through a scale, while the volume was assessed by analysing the displacement of the material within the container. The determined density was displayed on the digital screen of the densimeter. Each sample was subjected to an average of three readings.

Moisture Content

The moisture content test determines the quantity of water present in the sample. This test was essential for evaluating the quality and efficacy of mycelium composites, as the moisture content of the composites significantly impacted their mechanical properties. The samples were weighed using an analytical balance. The weight of the sample was recorded at various oven temperatures before and after placing the sample in the oven. The moisture content was then calculated using the formula given in Equation 1.

$$\text{Moisture content (\%)} = \frac{Wet\ weight - Dry\ weight}{Wet\ weight}\ x\ 100\% \qquad [1]$$

The wet weight represents the sample's initial weight, whereas the dry weight indicates the sample's final weight after drying. The moisture content results were recorded for each sample, and the average moisture content was calculated.

Shrinkage Measurement

The shrinkage test is important to target the specific product dimension. The initial dimensions of the sample were 155 × 155 × 10 mm. The sample was placed in an oven (model: Protech GOV-50D). As drying progresses, the moisture content of the sample decreases, causing the sample to shrink. Once the drying period was finished, the final dimensions of the sample were measured. Excessive shrinkage could lead to deformations, fractures and dimensional inconsistencies, all of which could affect the performance and suitability of the material. The formula shown in Equation 2 is used to determine the percentage of shrinkage for each dimension. Five readings were taken for each sample, and the average was recorded.

$$\text{Shrinkage (\%)} = \frac{Initial\ dimension - Final\ dimension}{Initial\ dimension}\ x\ 100\% \qquad [2]$$

Macroscopic Observation

A macroscopic observation was conducted to observe the physical alteration of the sample. The photos were taken to document the transformation of mycelium composites, from their state prior to drying to their state after drying (as final products).

Scanning Electron Microscope (SEM)

The sample, which measures 10 x 10 mm, was cut to expose its internal structure, thus ensuring a clean and flat surface. Subsequently, the prepared sample was subjected to a Scanning Electron Microscope (SEM), specifically the TM3030 Tabletop Microscope with SwiftED3000. The SEM images obtained were subsequently analysed to assess the sample's microstructural properties.

Flexural Test

Samples measuring 72 × 13 mm from various oven temperatures were cut to perform a flexural test. A universal testing machine (UTM) Shimadzu AG-IS was utilised and fitted with a three-point bending test configuration. A constant crosshead speed of 2 mm/min and a clamp support distance of 80 mm were used. Following the conclusion of testing, the collected data were analysed. The flexural stress, flexural strain and other relevant mechanical properties, such as the modulus of elasticity and flexural strength, were determined and measured. The test was repeated five times, and the average value was recorded.

Impact Test

An impact test was carried out using a Dynatup 8250-drop weight impact machine to measure the maximum load of mycelium composite. The specimen was 100 × 100 mm.

RESULTS AND DISCUSSION

Density and Weight Measurement

Figure 2 depicts the density and weight of mycelium composite as a function of oven temperature. The density measurement followed the same pattern as the weight measurement.

The density of the mycelium composite decreased as the oven temperature was raised from 40°C to 60°C but then slightly increased at 80°C. The highest density was 0.17 g/cm^3 at 80°C and the lowest was 0.15 g/cm^3 at 60°C. Increasing the oven temperature caused moisture within the composite to evaporate, reducing weight. The composite's mass and volume decreased due to the loss of moisture and other volatile components, resulting in a lower density. When the composite is dried at 80°C, the water content of the mycelium hyphae rapidly evaporates. It causes the cell walls of the hyphae to contract and come into closer contact, which lowers porosity and boosts the density of the composite. The density of the prepared mycelium composite was found to be 0.15 to 0.17 g/cm^3, which was close to the results of 0.094 to 0.350 g/cm^3 reported in some literature (Elsacker et al., 2019; Peng et al., 2023). It was lower than the density of PS (1.04 g/cm^3), which was used as traditional packaging (Manan et al., 2021).

In terms of volume measurement, as moisture is removed during drying, the volume of the composite decreases due to the contraction of the composite as water evaporates. The degree of volume reduction depends on the initial moisture content and the drying temperature. Higher temperatures led to faster moisture removal and, consequently, greater shrinkage and volume reduction. It is evident in Table 3, which shows a decrease in the final volume of the composite as the drying temperature increases from 40°C to 80°C.

Meanwhile, for density measurement, the density of the sample is influenced by its mass and volume. While the mass decreases due to moisture loss, the volume also decreases due to shrinkage. The net effect of these changes on density depends on the relative mass and volume reduction rates. In this study, the composite density decreased as the oven temperature increased from 40°C to 60°C, indicating that the volume reduction outpaced the mass reduction. However, at 80°C, the density slightly increased, suggesting that the mass reduction became more significant than the volume reduction at this higher temperature. It could be attributed to the collapse and compaction of the hyphal structure due to excessive drying.

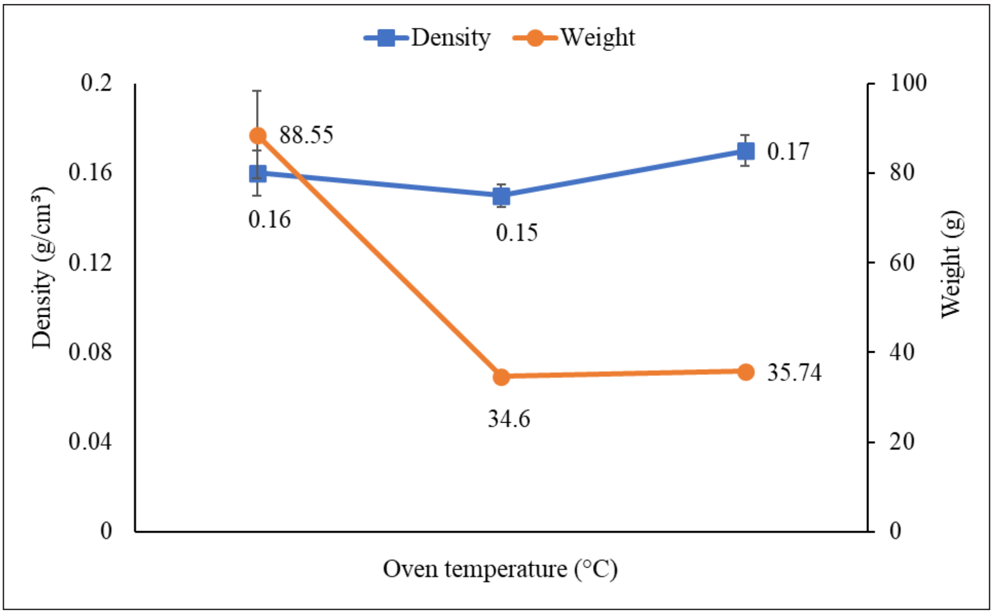

Figure 2. Density and weight of mycelium-based composite at various oven temperatures

Moisture Content

The oven's temperature plays a crucial role in determining the moisture content of the mycelium composite. Figure 3 displays the moisture content of the mycelium composite at different oven temperatures. A clear trend of decreasing moisture content was observed as the oven temperature increased. The composite subjected to 40°C exhibited the highest moisture content, which measured 63.53%. The moisture content decreased to 26.13% and 24.06%, respectively, as the oven temperature was increased to 60°C and 80°C. Inadequate moisture elimination during low-temperature drying of mycelium composite causes the mycelium composite to retain more moisture, thereby becoming wet. It slows down the rate of moisture evaporation, thereby reducing the loss of water from the composite. It causes the composite to become soft and pliable, increasing the risk of contamination because bacteria and other pathogens thrive in damp environments (Yang et al., 2021). Furthermore, a slower dying process, low temperatures, and high moisture content resulted in moisture expansion within the composite. The expansion can result in internal stresses, ultimately decreasing the composite's mechanical properties. It is evident in the study where the composite dried at 40°C exhibited the highest moisture content (63.53%) and the lowest values for impact load (335.80 N), flexural strength (0.05 MPa) and stiffness (2.66 GPa).

As the temperature increases to 60°C, higher temperatures promote faster evaporation of moisture, which leads to a decrease in moisture content. Increasing the oven temperature transfers heat energy to the water molecules within the composite, elevating their kinetic energy and facilitating faster evaporation. The moisture content decreased as the drying temperature increased, increasing stiffness and strength. However, excessive drying at 80°C accelerates moisture evaporation from the composite, rapidly removing water from the hyphal cell walls. It can cause the cell walls to shrink and collapse, weakening the overall structure. The weakened cell walls are less able to withstand mechanical stress, leading to a decrease in the mechanical properties of the composite. The loss of structural integrity can make the composite more brittle and prone to cracking or fracturing under stress.

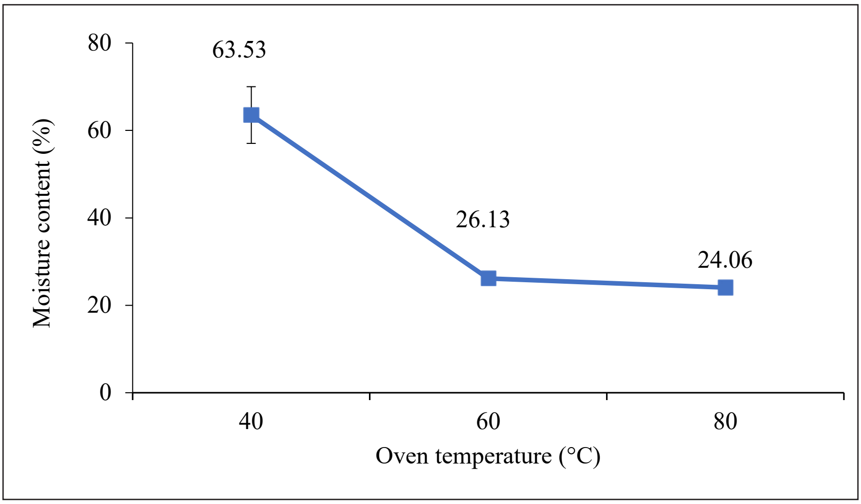

Figure 3. The moisture content of the mycelium composite was measured after drying at various oven temperature

The above result shows that high moisture content decreased mechanical strength and increased susceptibility to contamination, while excessively low moisture content made the composite brittle. Therefore, controlling the drying temperature is essential for achieving an optimal moisture content and optimising the mechanical properties of mycelium composite.

Shrinkage Measurement

Shrinkage is important for controlling the dimensions during drying, affecting the composite's dimensional stability. The shrinkage of the composite increased as the oven temperature extended, as presented in Figure 4. The sample subjected to 80°C observed the highest shrinkage, which was 23.2%. However, the shrinkage progressively decreased as lower oven temperatures were used. For example, the composite exposed to a temperature of 60°C showed a shrinkage percentage of 20.73%, whereas the composite exposed to a temperature of 40°C experienced a shrinkage of 13.49%. The trend aligns with the measurement of moisture content. As moisture evaporates, the composite contracts, leading to shrinkage and changes in the overall dimensions that potentially cause warping or cracking. At lower temperatures (40°C), the mycelium composite undergoes minimal shrinkage, indicating that it retains its original dimensions relatively well. Lower temperatures slow down the rate of moisture loss and decrease the likelihood of substantial contraction in the material. As the temperature increases to 60°C, shrinkage increases to 20.73%, and at 80°C, it peaks at 23.2%. This progressive increase in shrinkage with temperature indicates a loss of dimensional stability as the composite undergoes greater contraction due to moisture loss. When the composite is exposed to high temperatures, the moisture contained within it may start evaporating faster, causing it to dry.

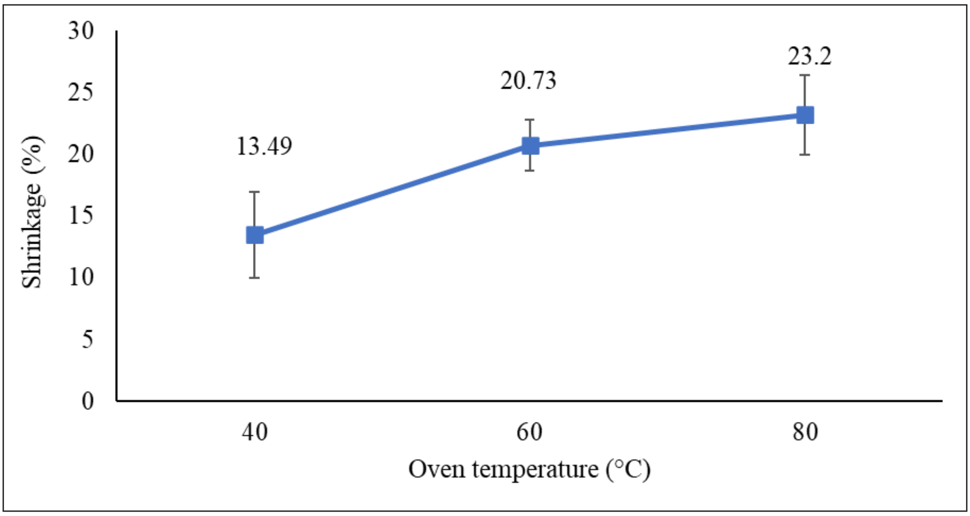

Figure 4. Shrinkage of a mycelium-based composite at various oven temperatures

As the moisture content increases rapidly, the spaces left behind by the evaporated water may become squeezed, resulting in the contraction of the composite and causing a reduction in its overall dimension. The decrease in the volume of the composite contributes to higher shrinkage. Moreover, elevated temperature can enhance the occurrence of particular chemical reactions, leading to the decomposition of specific constituents in the mycelium composite. These chemical reactions result in the production of volatile by-products, the emission of gases, or the reconfiguration of molecular structures, thereby causing a slight increase in shrinkage (Sydor et al., 2022). The increased shrinkage at higher temperatures can lead to warping, cracking and internal stresses, which can compromise the structural integrity and functionality of the composite. Therefore, while higher temperatures may accelerate the drying process, they also negatively impact the dimensional stability of the composite due to increased shrinkage.

The relationship between drying temperature and shrinkage in mycelium composite is directly proportional. While higher drying temperatures can expedite the drying process, they also lead to increased shrinkage, which can negatively affect the dimensional stability and structural integrity of mycelium composite.

Macroscopic Observation

Table 2 displays the image of the mycelium composite both before and after undergoing drying, with an increase in oven temperature. Drying the composite in an oven at a lower temperature causes it to shrink less, whereas drying it at higher temperatures can cause it to shrink more. When the moisture evaporates, the volume occupied by water decreases, which causes it to shrink. The reduction in volume is due to contraction. As a result, shrinkage causes a reduction in the volume of the composite, resulting in alterations in the dimensions of the composite, as shown in Table 3. The trend aligns with the measurement of shrinkage. At lower temperatures (40°C), the drying process is slower, allowing for gradual moisture removal and minimal shrinkage. This results in less internal stress within the composite, reducing the likelihood of warpage. However, as the drying temperature increases, the rate of moisture evaporation also increases. At 80°C, the rapid moisture loss causes significant shrinkage and internal stresses, making the composite more susceptible to warping.

Additionally, the high temperature can lead to the degradation of the hyphal cell walls, which are essential for the material's structural integrity. This degradation results in a decrease in flexural strength and flexural modulus, making the composite weaker and less resistant to bending forces. Additionally, thermal degradation can cause discolouration (yellowish) and warping of the composite, further compromising its mechanical performance and aesthetic appeal. At the same time, warpage is also observed, which causes the composite to deviate from its intended flat form. This warpage is a result of the composite's low stiffness. Warpage can increase stress on the mycelium composite, causing it to shrink more during drying. As a result, to keep the shape and dimensions of the composite, the oven temperature should not be raised any more.

Table 2
Mycelium composite at various oven temperatures: (a) 40°C, (b) 60°C, and (c) 80°C

Oven temperature (°C)	Before drying in the oven (After incubation)	After drying in the oven
40		 
60		 
80		 

Table 3
The dimensional and volume changes of the mycelium composite were observed after drying at various oven temperature

Oven temperature (°C)	**Sample**	**Final length (mm)**	**Final width (mm)**	**Final height (mm)**	**Volume (mm^3)**	
					Initial (Before drying)	**Final (After drying)**
40	1	145	150	10	240250	217500
	2	140	145	10	240250	203000
	3	140	145	10	240250	203000
Average		141.67	146.67	10	240250	207833
60	1	138	135	10	240250	186300
	2	140	140	10	240250	196000
	3	138	137	10	240250	189060
Average		138.67	137.33	10	240250	190453
80	1	135	140	10	240250	189000
	2	135	140	10	240250	189000
	3	132	133	10	240250	175560
Average		134	137.67	10	240250	184520

Remarks. The initial length*width*height of sample = 155 × 155 × 10 mm

Scanning Electron Microscope (SEM)

Figure 5 shows the morphological modifications to the structure of the composite between the network structure of hyphae at various oven temperatures. Drying at low temperatures preserves the structure of the mycelium composite. At 40°C, the SEM images (Figure 5a) show a loosely packed hyphal network with low interconnectedness. The hyphae strands appear thin, with visible gaps and voids between them. Lower temperatures slow the drying process, leading to higher moisture retention in the mycelium. This results in a less interconnected hyphal network with a lower degree of fusion between hyphae strands. The hyphae appear less densely packed, resulting in a porous structure contributing to the lower strength of the mycelium composite, as evidenced by the low flexural strength (0.05 MPa) observed in the study. Increasing the drying temperature to 60°C leads to a denser and more interconnected hyphal network (Figure 5b). The hyphae strands appear thicker and more tightly packed, with fewer voids and gaps. As the drying temperature increases to 60°C, the rate of moisture removal accelerates, which results in a significant removal of water from the cell walls. It leads to a denser packing of hyphae and a higher degree of interconnectedness within the network. The high packing of hyphae creates a more interconnected structure, as high shrinkage causes the hyphae to come into closer contact.

As a result, the cell walls may start to fuse, resulting in a stronger and more compact composite structure. This improved the mechanical properties observed at this temperature,

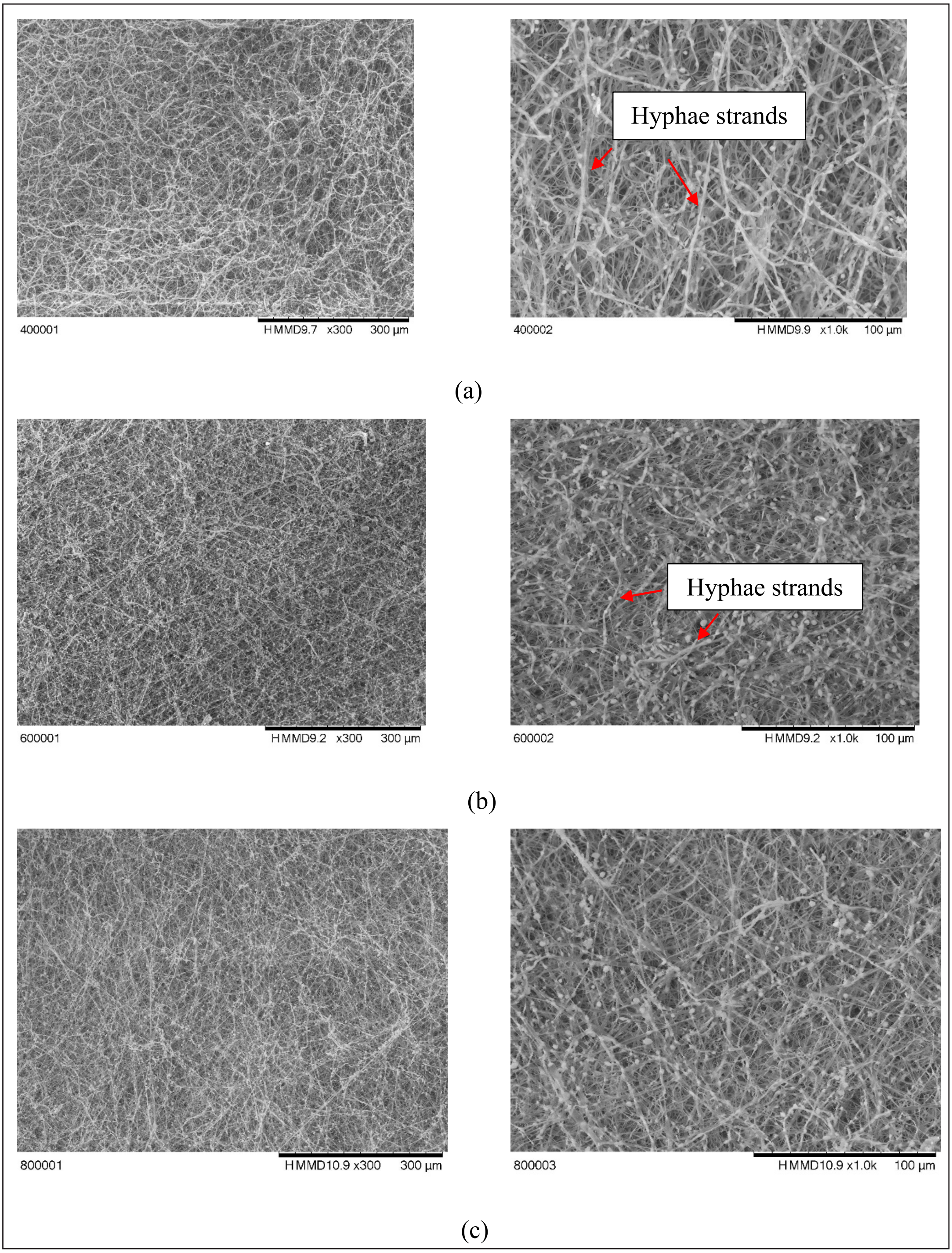

Figure 5. SEM image of mycelium showing the surface layer on composite at a magnification of 300× and 1000× at various oven temperatures: (a) 40°C, (b) 60°C, and (c) 80°C

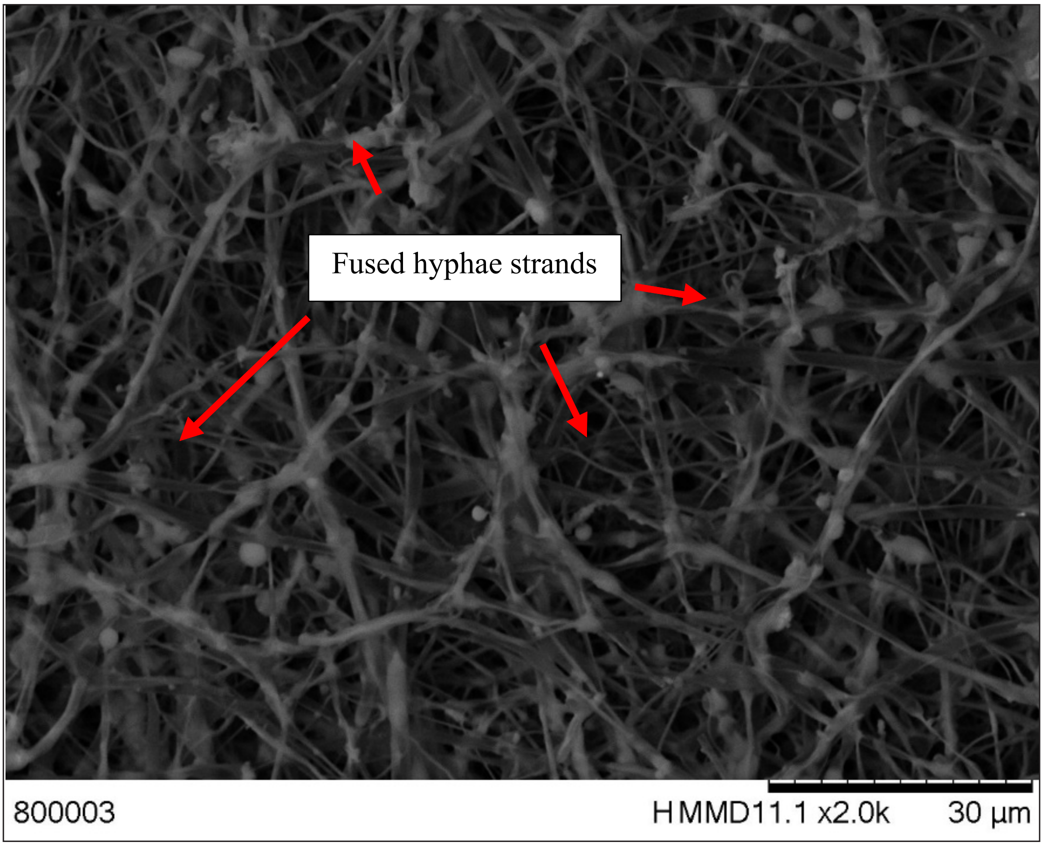

Figure 6. Morphology of mycelium composite at 80 °C with magnification of 2000×

with flexural strength increasing to 0.11 MPa and flexural modulus to 4.15 GPa. The higher magnification image (Figure 6) further reveals the fusion of hyphae strands, creating a more continuous and robust network that can effectively distribute stress and resist deformation, resulting in high mechanical properties. It also reduces localised strain and minimises the occurrence of warping. At higher drying temperatures, the rapid moisture loss causes significant shrinkage and further fusion of the hyphae strands, forming an interconnected network of hyphae. When the hyphae strands fuse and become tightly packed, primarily due to the substantial water loss, they decrease the porosity and occupy a smaller volume, resulting in increased composite density. The increased density affects the weight of the composite. However, excessive drying can lead to the degradation of the hyphal cell walls, potentially compromising the structural integrity of the composite and further increasing the temperature to 80°C, resulting in an even denser hyphal network with signs of degradation (Figure 5c).

The hyphae strands appear fused and compacted, but some have collapsed or broken. This degradation is likely due to the excessive heat causing damage to the hyphal cell walls. The cell walls of mycelium shrink more and contract due to the removal of water, resulting in intense drying. These cell walls, primarily composed of polysaccharides like chitin, glucans, or cellulose, are essential for maintaining the composite's structure and strength. Cell walls experience a loss of turgidity and undergo inward compression due to decreased internal pressure. When turgor pressure is decreased, the cell walls undergo degradation, resulting in reduced rigidity and a tendency to collapse. This phenomenon has the potential to result in the deterioration of its inherent structural integrity. While the composite still exhibits relatively high flexural strength (3.64 MPa) and modulus (0.09 MPa), the slight decrease compared to the 60°C suggests that the structural damage caused by the high temperature begins to outweigh the benefits of increased density. Therefore, properly controlling the drying temperature is essential to preserve the mycelium's structural integrity.

Flexural Test

Figure 7 shows the relationship between oven drying temperature and the flexural properties (strength and modulus) of mycelium composites. An initial increase in both flexural strength and modulus is observed as the temperature rises from 40°C to 60°C. However, a further increase in temperature to 80°C leads to a slight decrease in both properties. At lower drying temperatures (40°C), the flexural strength (0.05 MPa) and flexural modulus (2.66 MPa) are relatively low. It is attributed to the loose packing of hyphae and a low degree of interconnectedness within the hyphal network. The gaps and voids between the hyphae strands weaken the overall structure, making it less resistant to bending forces. The flexural strength (0.11 MPa) and flexural modulus (4.15 GPa) peak at 60°C indicate a strong bond between the mycelium and substrate particles, enhancing interfacial adhesion. This bonding has the potential to increase the flexural strength and modulus. This can be explained by the fact that mycelium and its associated compounds are more likely to diffuse at higher temperatures during drying. It allows the mycelium to penetrate deeper into the substrate particles and promotes intimate contact between the mycelium and the substrate surface. Mycelium's increased diffusion and penetration into the substrate results in a larger contact area and stronger bonding.

Additionally, a denser and more interconnected hyphal network, with increased fusion between hyphae strands, helps to distribute the stresses and loads uniformly. However, when it reached 80°C, the mycelium composite's flexural strength (0.09 MPa) and modulus (3.64 GPa) decreased. This decrease is likely due to the excessive heat causing degradation of the hyphal cell walls, reducing its load-bearing capacity and structural integrity. The degradation of mycelium composites can also be attributed to various factors, including thermal degradation of both mycelium and the matrix material and moisture loss. The flexural strength and modulus obtained in this study exhibited a significant similarity to the results reported by Appels et al. (2019), who found flexural strengths ranging from 0.05 MPa to 0.29 MPa and flexural modulus varying from 1 GPa to 9 GPa in their investigation of mycelium composite.

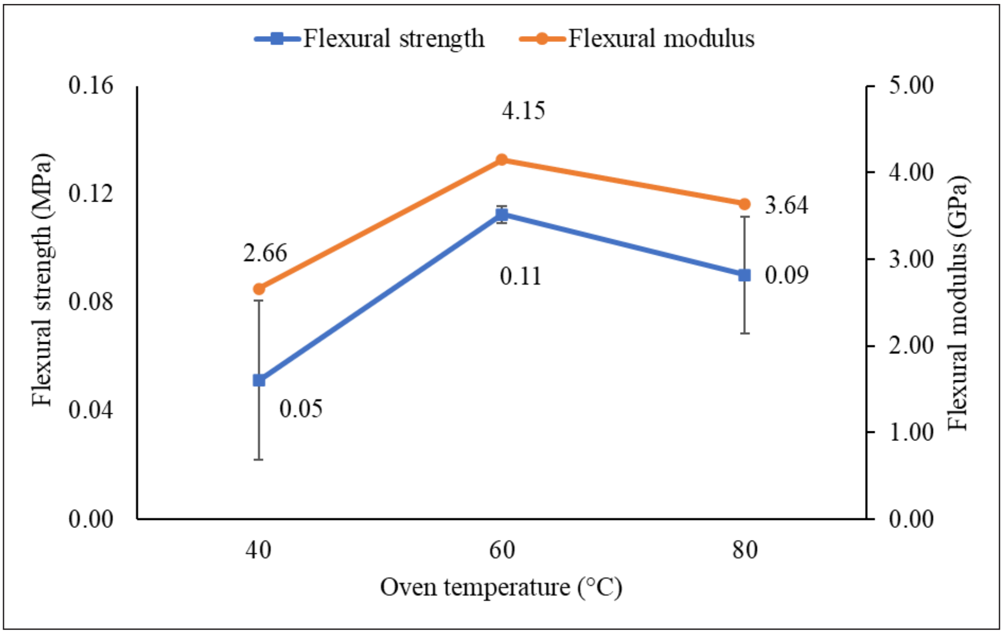

Figure 7. Flexural strength and modulus of mycelium-based composite at various oven temperature

Impact Test

The impact test results provide information about the ability of mycelium composites to withstand sudden loads, a key consideration for applications like packaging materials where impact resistance is vital. As shown in Figure 8, the impact strength of the composite significantly increases as the drying temperature rises from 40°C to 60°C. It suggests that higher temperatures enhance the material's ability to absorb and dissipate impact energy due to improved interfacial bonding and a more integrated structure. However, a slight decrease in impact strength is observed at 80°C compared to 60°C. It indicates that while higher temperatures initially improve impact resistance, excessive heat may lead to degradation within the composite, slightly reducing its ability to withstand impacts. The heat can cause degradation of the composite's molecular structure (hyphal degradation), resulting in the breakdown of intermolecular bonds and changes in the arrangement of its constituents. This degradation can weaken the composite and negatively reduce the load-bearing capacity of the mycelium composite.

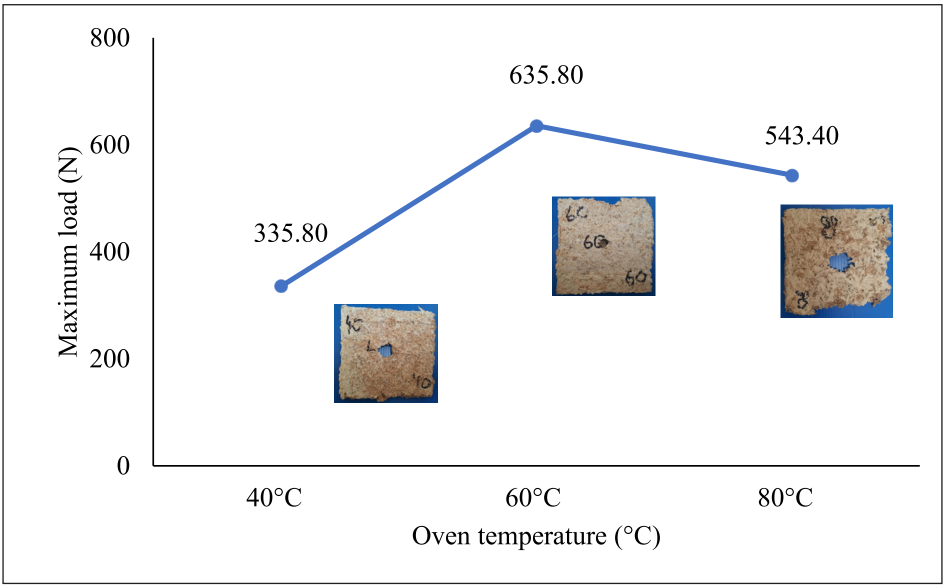

Figure 8. Maximum load of a mycelium-based composite at various oven temperatures

CONCLUSION

Significant morphological and mechanical changes were observed upon drying the mycelium composite at various oven temperatures (e.g. 40°C, 60°C, and 80°C).

The optimal drying temperature for mycelium composites is 60°C. This temperature strikes a balance between effective moisture removal and preservation of the composite's structural integrity.

At 60°C, the mycelium composite exhibits the highest flexural strength (0.11 MPa), flexural modulus (4.15 GPa), and maximum load (635.80 N) for impact test, indicating superior mechanical properties compared to composites dried at lower or higher temperatures. The drying process at 60°C resulted in a decrease in density. It is supported by the decrease in the density value from 0.16 g/cm^3 to 0.15 g/cm^3. The reduction in density can be attributed to removing moisture content during the drying process. It is corroborated by the finding that the mycelium composite's moisture content decreased from 63.53% to 24.06% after 24 hours of drying at 40°C and 60°C, respectively.

Although drying at higher temperatures, such as 80°C, contributes to faster moisture evaporation, the volume changes caused by rapid water removal can lead to greater shrinkage and the occurrence of warpage. It causes thermal stress, leading to the denaturation of polysaccharides and subsequent degradation and collapse of the hyphae. Discolouration also occurs due to thermal degradation at higher drying temperatures. In addition, a higher drying temperature of 80°C may contribute to an increase in density and weight as well as a decrease in mechanical properties.

FUTURE RECOMMENDATIONS

Based on this research's findings, several potential future research directions can be pursued to further optimise the drying process of mycelium composite.

Optimising the oven's drying temperature, duration, and airflow achieved the desired balance between moisture removal, shrinkage and mechanical properties. It could involve developing predictive models or using machine learning algorithms to identify optimal drying conditions for specific applications.

Investigating alternative drying methods, such as microwave drying, vacuum drying, or hybrid approaches, could lead to more effective drying techniques.

Investigating pre-drying or pre-heating could improve the uniformity of the oven-drying process and influence the final properties of the mycelium composite.

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