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Research Article

Eco-Friendly Biocomposites Reinforced with Sulfur Mushroom: Impact on Thermophysical Properties and Structural Integrity

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Abstract – This study was conducted on the production and characterization of biocomposite materials reinforced with sulfur mushrooms (*Laetiporus sulphureus*). The thermophysical properties of the produced biocomposites, such as bulk density, Shore A hardness, thermal conductivity coefficient, and surface morphology, were characterized. Sulfur mushroom was integrated into the biocomposite matrix as a biodegradable and renewable additive material. Dried and ground sulfur mushroom was added to the raw material in powder form at 1 wt.%, 2 wt.%, 3 wt.%, and 4 wt.%. Commercial polyol (CP) and castor oil (CO) were used as raw materials. Methylene diphenyl diisocyanate (MDI) was preferred as a crosslinker. The results show that sulfur mushroom raises the hardness of biocomposites and slightly increases the thermal conductivity coefficient. In Fourier-transform infrared (FTIR) spectra, it is understood that sulfur cork physically interacts with CP and CO and MDI forms a chemical bond. The surface porosity of the biocomposite was not adversely affected up to 2 wt.% (optimum ratio). However, reinforcement of the biocomposite with high biomass filler raised the bulk density and Shore A hardness. It has been observed that it improves the structural integrity and lightness of the material. The use of such additives and fillers in obtaining a low carbon footprint, environmentally friendly, and economical biocomposites will make significant contributions in the future.

Keywords – Laetiporus sulphureus, castor oil, biocomposite materials, thermophysical properties, characterization

I. INTRODUCTION

Today, environmental sustainability has become a priority in materials science and engineering applications. In this context, biocomposites obtained from renewable resources attract attention due to their low ecological impact and biodegradability. The use of biological materials such as natural mushrooms as reinforcing components in biocomposites allows the development of environmentally friendly products. The cellular structure of the sulfur mushroom offers advantages such as high mechanical strength, low density, and thermal insulation properties, which increase the usability of this material in biocomposites [1-3].

The use of mushrooms in biocomposites can improve thermophysical properties such as thermal conductivity, thermal expansion, and thermal resistance. Studies have shown that the mushroom structure increases the thermal insulation performance of biocomposites thanks to its low thermal conductivity. In addition, the natural polymers and microscopic porous structure contained in materials obtained from sulfur mushrooms reduce the coefficient of thermal expansion and increase the resistance of the materials to temperature changes [4-6].

Including mushrooms in biocomposites can also provide positive results in terms of mechanical durability. In particular, the natural fibers and cellular structure of sulfur cork provide elasticity and impact resistance to biocomposites. In addition, it reduces the density of biocomposites and enables the creation of lightweight but robust structures. These features increase the potential for use of such materials in the construction, automotive, and packaging sectors [7-9].

In studies conducted in the literature, biocomposite materials have been developed using sulfur cork (*Laetiporus sulphureus*). Such natural organic reinforcements also offer advantages in environmental and economic dimensions. Low-cost mushroom-based biomaterials do not harm the environment in waste management since they are biodegradable. Biocomposites reinforced with sulfur cork have great potential, especially in applications requiring energy efficiency. Their thermal insulation properties make these materials ideal for building insulation and low-energy consumption devices. In addition, they offer usage opportunities in the automotive and aviation industries thanks to their lightness and durability. The aesthetic and environmental advantages of these materials also make them preferred in sustainable packaging and furniture design [10-12].

The development of biocomposites reinforced with sulfur fungus stands out as a significant innovation in the field of environmentally friendly materials production. However, further research is needed on the challenges of large-scale production of these materials and their long-term durability performance. Future studies can develop new methods to expand the applications of these materials in various industries and optimize their performance [13-15].

In this study, the production and characterization of polyurethane-based biocomposite materials reinforced with sulfur mushroom (*Laetiporus sulphureus*) were carried out. In the study, the properties such as bulk density, Shore A hardness, thermal conductivity coefficient, and surface morphology of biocomposites obtained by using sulfur mushrooms as a biodegradable and renewable additive were investigated in detail. The study aims to understand the effects of different amounts of sulfur mushroom additive on the thermophysical and mechanical performance of biocomposites. The findings obtained contribute to the development of environmentally friendly, low carbon footprint and economical biocomposites, offering significant potential in the fields of sustainable biomaterials and green technology [16-18].

II. MATERIAL AND METHOD

This study aims to produce and characterize biocomposite materials reinforced with sulfur mushrooms (*Laetiporus sulphureus*). Commercial polyol (CP) and castor oil (CO) were used as raw materials in the production of biocomposites, and methylene diphenyl diisocyanate (MDI) was preferred as a crosslinker. Sulfur mushroom was included in the biocomposite matrix as a biodegradable and renewable additive material. For the sulfur mushroom to be properly integrated, the mushroom was first dried (Figure 1) and then ground into a fine powder (Figure 2). The prepared sulfur mushroom powder was added to the raw material mixture at 1 wt.%, 2 wt.%, 3 wt.%, and 4 wt.%. These ratios were designed to determine the optimum performance and properties of the biocomposites.

During the preparation of the raw material mixture, CP and CO (1 wt.%) were combined at specified ratios to obtain a homogeneous mixture. Sulfur mushroom powder was added to this mixture at specified ratios and mixed thoroughly. MDI, used as a crosslinker, was added to the prepared mixture in a controlled manner and the chemical reaction was ensured. After the mixture was homogenized, it was poured into the specified molds and cured under appropriate temperature and pressure conditions. The curing process was optimized to stabilize the mechanical and thermophysical properties of the biocomposite.

A series of characterization methods were applied to determine the physical and thermal properties of the produced biocomposites. First of all, bulk density measurements were performed to determine the mass ratio of the produced biocomposites. Shore A hardness test was performed to measure the mechanical strength of the biocomposites. A thermal conductivity test was applied to measure the heat conduction coefficient, and how these values changed depending on the ratio of sulfur mushroom addition was analyzed. The material surface image was examined with a microscope, and the effects of the sulfur mushroom addition ratio on porosity and surface structure were evaluated in detail.

In addition, Fourier transform infrared (FTIR) spectroscopy was used to examine the chemical structure of the biocomposites. This analysis was performed to understand the physical and chemical interactions of sulfur cork with CP, CO, and MDI. The spectral data obtained showed that the sulfur mushroom was successfully integrated into the biocomposite matrix and did not form chemical bonds with MDI in physical interaction.

Figure 1. Image of sulphur mushroom *(Laetiporus sulphureus)* drying in the oven

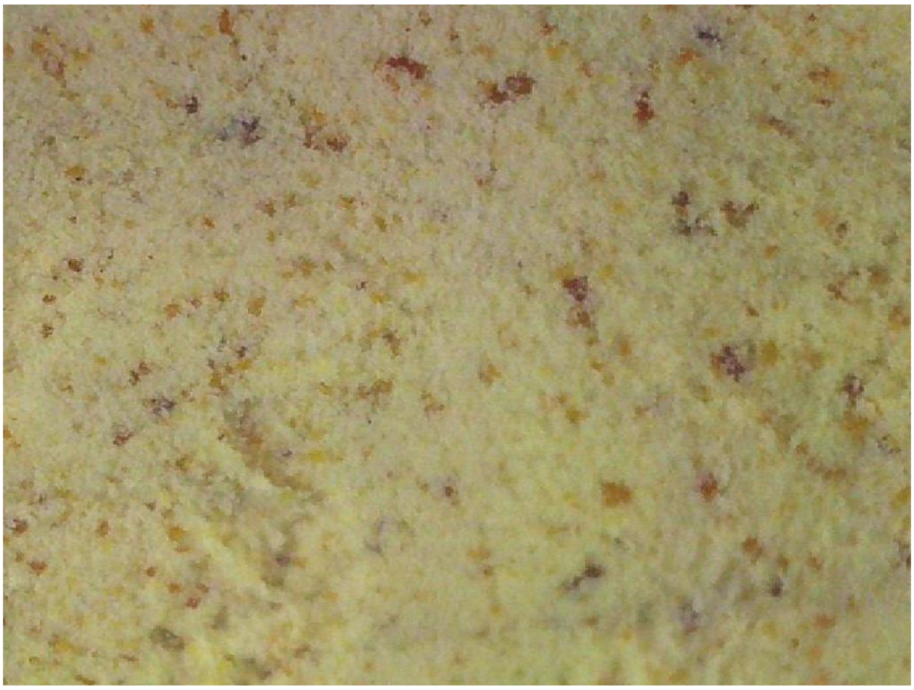

Figure 2. Microscope image of ground sulfur mushroom *(Laetiporus sulphureus)*

Figure 3 shows the biocomposite production scheme using sulfur mushrooms. In the first stage, it is very important to form a homogeneous mixture with commercial polyol and filler. In the second stage, castor oil (CO) and MDI are added and attention is paid to the optimum temperature and time of curing.

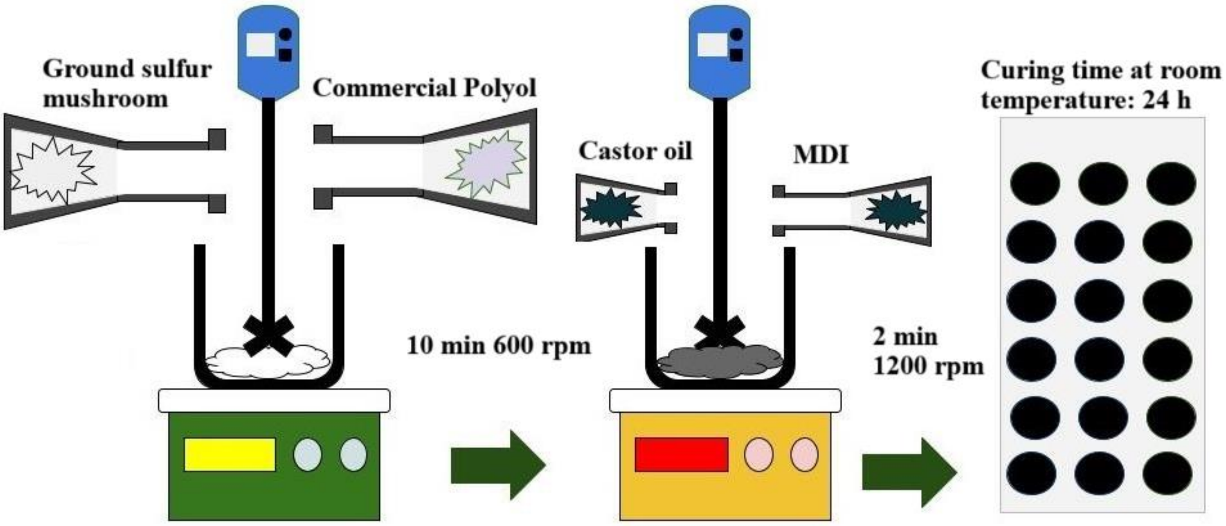

Figure 3. Production scheme of sulfur mushroom reinforced biocomposite biocomposite

III. RESULTS AND DISCUSSION

In this study, the effects of sulfur mushroom (*Laetiporus sulphureus*) addition on the bulk density and Shore A hardness of polyurethane-based biocomposites were investigated. The results obtained show that an increase in the bulk density of the biocomposite occurs with the rise in the sulfur mushroom ratio (Figure 4). This situation is related to the natural structure of the sulfur mushroom occupying more space in the matrix and increasing the density during its integration into the matrix. A significant rise in bulk density was observed especially at 3 wt.% and 4 wt.% ratios. However, a similar trend was observed in Shore A hardness values. The addition of sulfur mushroom to the matrix increased the surface strength of the composite and allowed a harder structure to be obtained (Figure 5). At low additive ratios (1 wt.% and 2 wt.%), the surface morphology remained homogeneous, and a gradual increase in hardness values was observed. However, the increase in hardness value became more pronounced at 3 wt.% and above ratios, indicating that the amount of filler material in the matrix reached a critical level. These findings obtained from the Shore A hardness test reveal that mechanical strength of biocomposite can be optimized with sulfur mushroom addition.

The effect of sulfur cork addition on the thermal conductivity coefficient of polyurethane-based biocomposites was investigated to understand the thermal performance of the material. Since sulfur mushroom is a natural material with low thermal conductivity, a slight rise in thermal conductivity coefficient was observed with its addition to biocomposite (Figure 6). This situation is related to the presence of sulfur mushroom as a filler material in the matrix and the change in microporous structure affecting thermal conductivity in the matrix. However, in additions up to 2 wt.%, the change in thermal conductivity coefficient was quite limited and the thermal insulation properties of the biocomposite were largely preserved. At higher addition ratios (3 wt.% and 4 wt.%), a slight increase in thermal conductivity coefficient was recorded, but this increase was not at a level that would negatively affect the overall thermal performance of the biocomposite. These findings indicate that sulfur mushroom additives can increase the usability of biocomposites in a wide range of applications by providing a balanced structure in terms of both mechanical and thermophysical properties [19-21].

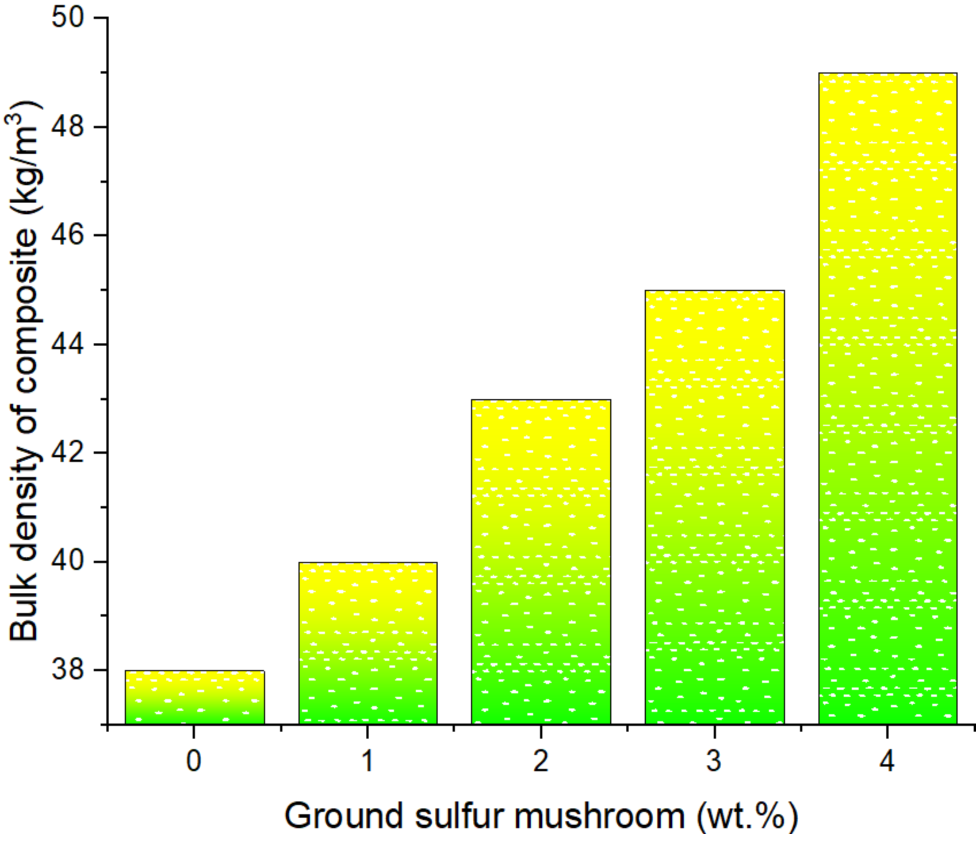

Figure 4. Effect of sulfur mushroom reinforcement on bulk density of biocomposite

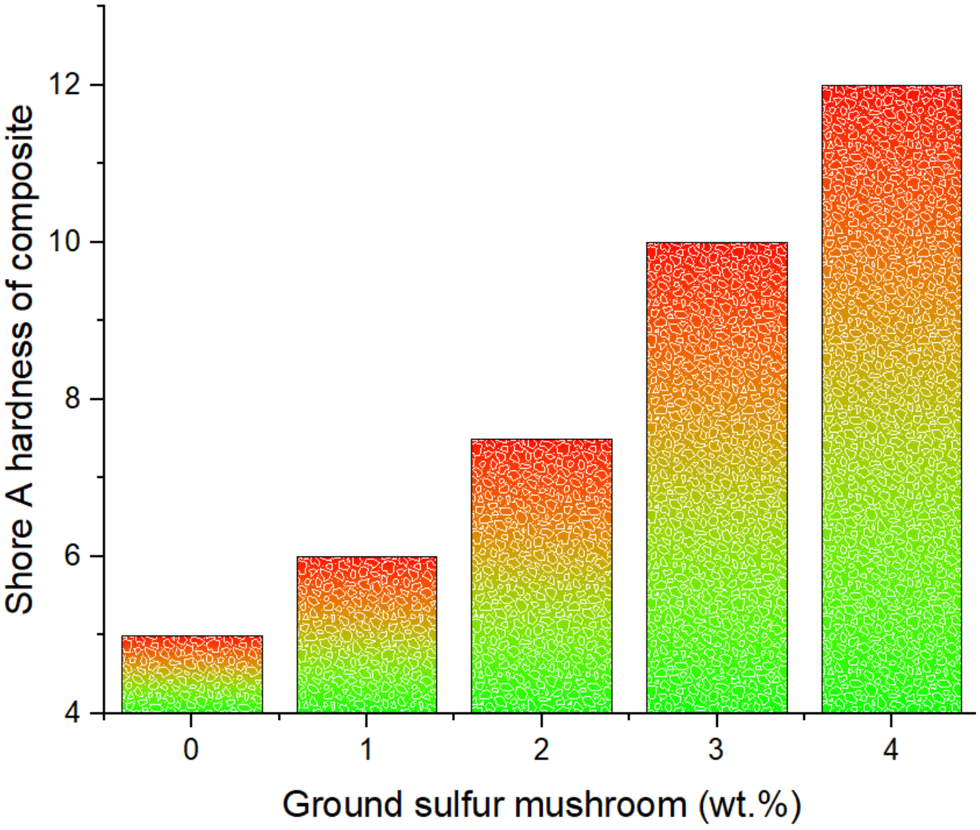

Figure 5. Effect of sulfur mushroom reinforcement on Shore A hardness of biocomposite

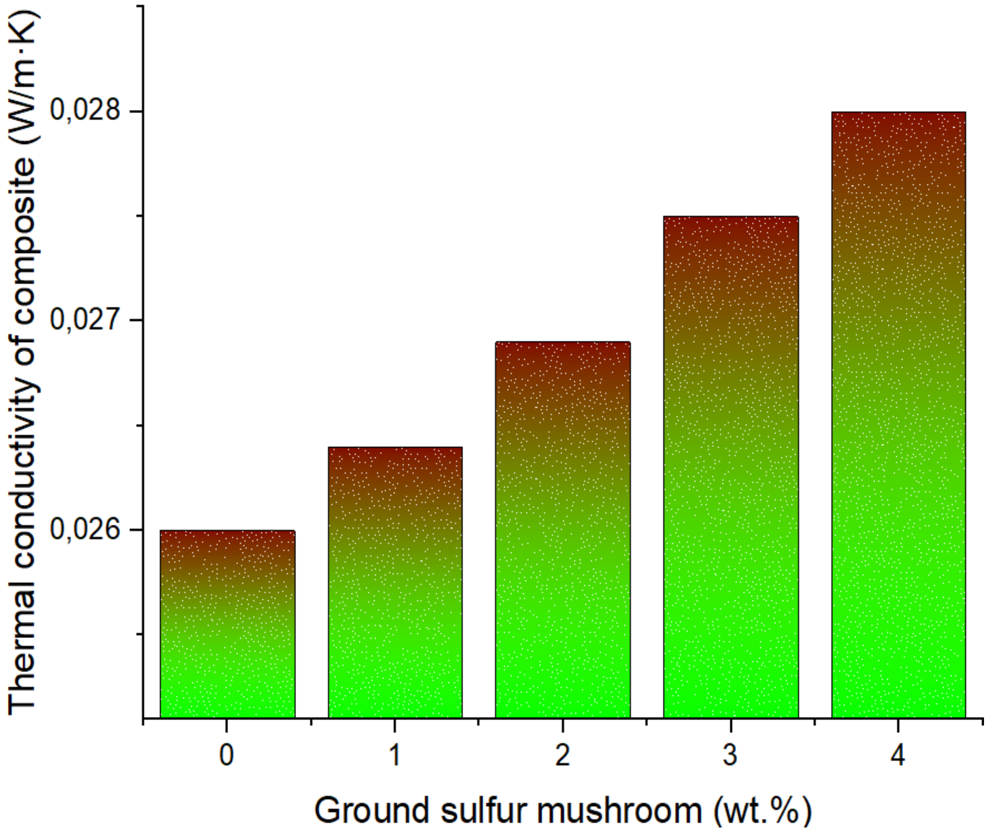

Figure 6. Effect of sulfur mushroom reinforcement on thermal conductivity coefficient of composite

In this study, polyurethane production is carried out by the chemical reaction between methylene diphenyl diisocyanate (MDI) and polyether polyol. The FTIR (Fourier transform infrared) spectrums of the polyurethane formed as a result of this reaction reveal the structural components of the material and the characteristic peaks that confirm the successful completion of the reaction. Figure 7, the absorption bands belonging to the isocyanate (-NCO), carbonyl (C=O), amine (-NH), and ether (-C-O-C-) groups in the polyurethane structure are remarkable. The characteristic peaks belonging to the isocyanate groups are generally seen in the wavelength range of 2230-2265 cm^{-1}. The disappearance or decrease in the intensity of these peaks when the reaction is completed indicates that MDI is consumed by reacting with the polyether polyol. The carbonyl (C=O) stretching vibrations of the formed urethane bonds show themselves as a strong peak in the region of approximately 1705-1725 cm^{-1}. This peak is a basic sign confirming the formation of the polyurethane structure. In FTIR spectra, absorptions of amine groups released during the formation of urethane bonds are generally observed as a broad band in the range of 3250-3450 cm^{-1}. This band reflects the tendency of -NH groups to hydrogen bond and chemical interactions in the polyurethane structure. In addition, characteristic peaks of ether groups in the polyurethane structure become apparent in the range of 1000-1200 cm^{-1}. In addition, hydroxyl (-OH) bonds are observed in the wavelength range of 3350-3550 cm^{-1}. These peaks indicate the presence of polyether polyol and the chain structure in the polyurethane matrix. FTIR analysis can also be used to evaluate microstructural features in the polyurethane structure, such as crosslinking and phase separation. For example, interactions between hard segments and soft segments can be understood through the displacement or broadening of carbonyl peaks. FTIR spectroscopy is a critical method for verifying the polyurethane structure, examining the efficiency of the reaction, and analyzing the microstructural properties of the material. FTIR spectra provide detailed information to assess the completeness of the reaction between MDI and polyether polyol and to detect bond formations in the polyurethane structure. These analyses allow optimization of the chemical structure, which is directly related to the mechanical and thermal performance of the produced polyurethane. In this research, ground and dried solid powdered sulfur fungi physically interact with the composite. It is understood from the FTIR spectra that they do not give a chemical reaction [22-24].

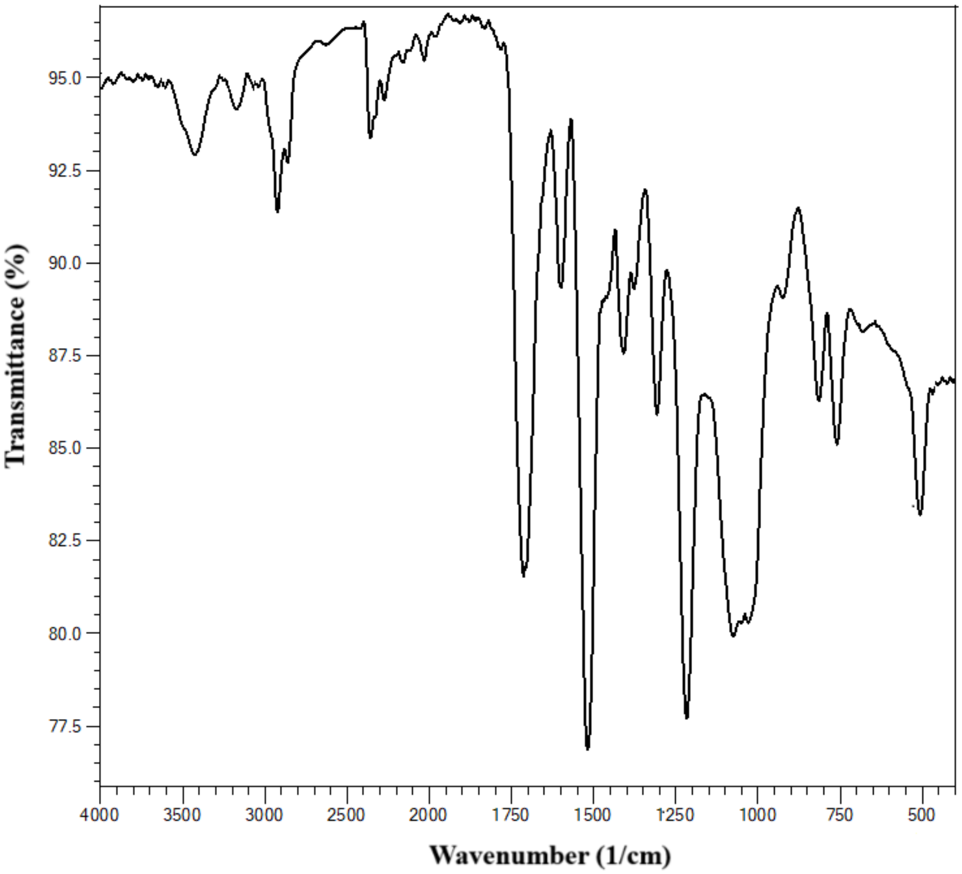

Figure 7. FTIR spectra of 2 wt.% sulfur mushroom-reinforced biocomposite

In this study, microscopic surface images of biocomposites reinforced with sulfur mushroom (*Laetiporus sulphureus*) were examined in detail. It aimed to evaluate the effects of the integration of sulfur mushrooms into the biocomposite matrix on surface porosity and homogeneity. Low ratios (1 wt.% and 2 wt.%) of sulfur mushroom additive showed that the surface exhibited a homogeneous structure and the pores were regularly distributed. At these ratios, it was understood that sulfur mushroom was homogeneously distributed in the biocomposite matrix and did not damage the integrity of the matrix. However, sulfur mushroom additives at 3 wt.% and 4 wt.% ratios led to partial agglomerations on the surface and increased porosity. This was associated with the difficulty of homogeneously dispersing sulfur mushroom powder in the matrix at high ratios. Microscope images revealed that sulfur mushrooms contributed to the formation of both micro-scale pores and cellular structures in the biocomposite. Thanks to the natural structure of the sulfur mushroom, the presence of micropores on the biocomposite surface was observed, which supported the lightness and thermal insulation properties of the material. In particular, it was confirmed that the 2 wt.% sulfur mushroom additive gave optimum results in terms of surface morphology and supported the thermophysical structure of the composites [25-27]. Figure 8 shows the microscopic image of the composite without sulfur mushroom and Figure 9 shows the microscopic image of the composite reinforced with 2% sulfur mushroom.

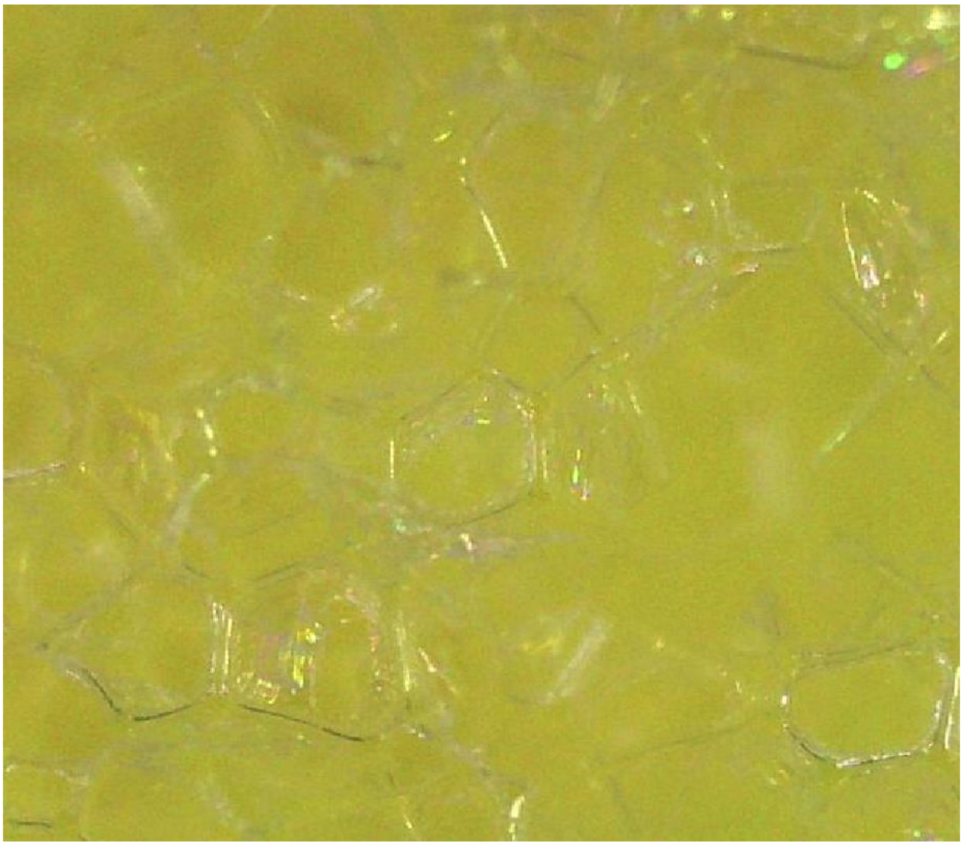

Figure 8. Microscopic image of the composite without added sulfur mushroom

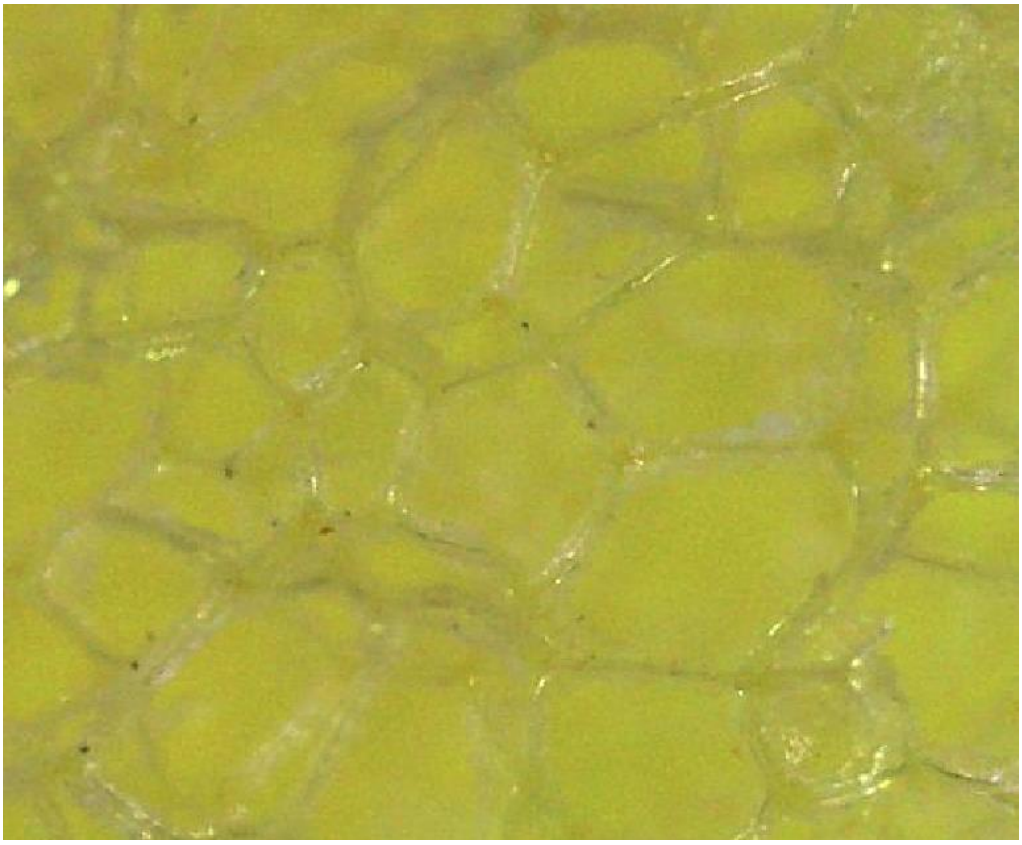

Figure 9. Microscopic image of the composite reinforced with 2 wt.% sulfur mushroom

Conclusions

This study was carried out on the production and characterization of biocomposite materials reinforced with sulfur mushroom (*Laetiporus sulphureus*). The findings obtained made significant contributions to the development of environmentally friendly, low carbon footprint and economical biomaterials. The integration of sulfur mushrooms into the biocomposite matrix as a biodegradable and renewable additive positively affected both the mechanical and thermophysical properties of the material. In the analysis, it was observed that the addition of sulfur mushroom increased the Shore A hardness of the biocomposites and slightly raised the thermal conductivity coefficient. However, the inclusion of sulfur mushrooms in the matrix at 1 wt.%, 2 wt.%, 3 wt.%, and 4 wt.% ratios created different effects on surface porosity and structural integrity. In particular, it was determined that 2 wt.% was the optimum additive amount. It was understood that the hardness, density, and thermal properties of the biocomposite were improved with the optimum ratio without adversely affecting the surface porosity of the biocomposite. Higher ratios (4%) of sulfur cork additives may negatively affect the pore distribution and diameter of the composite. It has been shown that biocomposites show a suitable performance in terms of thermal conductivity while maintaining their lightness and strength properties. This proves that sulfur mushroom additives are a versatile reinforcement material that increases the usability of biocomposites in different industrial applications.

As a result, the development of biocomposites reinforced with sulfur cork is considered an important step towards environmentally friendly material production and sustainability goals. The fact that sulfur cork can be easily obtained from renewable resources and its low cost further increases the economic and environmental advantages of these materials. In the future, research and applications aimed at large-scale production of such biocomposites will be critical to optimize material performance and develop sustainable engineering solutions. Such research is a guide in the development of innovative and environmentally friendly biomaterials.

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