Exploring the potential of Australian agricultural and industrial wastes from the source to bio-fabricating viable mycelium-based composites

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Abstract- Australia generates approximately 75.8 million tonnes of waste annually, with significant contributions from biomass produced by agricultural and industrial activities. This study evaluated the potential of transforming underutilised Australian biomass waste, such as hemp hurd, mulch, bagasse, and sawdust from factory mills and agricultural sources, to develop mycelium-based composites (MBCs) for applications in construction and interior design. This is one of the first studies to explore the potential of the Australian Reishi fungus (*Ganoderma steyaertanum*) species in bio-fabricating MBCs from local biomass waste directly sourced from sugar mills, golf courses and furniture factories. The MBCs were assessed using volume and weight measurements, compressive strength testing and SEM imaging analysis. Results indicated that MBC derived from mulch exhibited the highest density and compressive strength, rendering them suitable for non-load-bearing construction and interior applications. Bagasse- and hemp-based MBCs have potential applications in insulation and acoustic panels. In contrast, sawdust-based MBCs face challenges due to chemical contaminants, including microplastics and formaldehyde. This research underscores the opportunity to convert low-value biomass into high-value materials, thereby supporting sustainable practices, reducing carbon emissions in Australia, and promoting the principles of a circular economy.

Keywords: Mycelium-based composite, agricultural and industrial waste, circular economy, bio-fabrication, Australia.

1 Introduction

Australia generates approximately 75.6 million tonnes (Mt) of waste annually [1], with significant contributions from the agricultural and industrial sectors. Organic waste, particularly biomass, accounts for

14.6 Mt of this total in 2022-23 [1]. During the same period, the commercial and industrial sectors contributed 33 Mt, construction and demolition accounted for 29 Mt, and municipal solid waste was 13 Mt [1]. A substantial portion of this organic waste, such as sugarcane bagasse, sawdust, mulch, and other plant residues, is either incinerated for energy production (e.g., in sugar mills), disposed of in landfills, or left to decompose naturally. These conventional disposal methods represent a loss of potentially valuable material and contribute significantly to atmospheric carbon dioxide (CO_2) emissions, exacerbating climate change.

Mycelium-based composites (MBCs) are biodegradable materials formed through the growth of fungal mycelium—specifically, the vegetative root-like structure of fungi—on lignocellulosic substrates, which may offer an alternative for repurposing Australian biomass waste into viable bio-based materials for various applications. MBCs are emerging as a promising option for the development of bio-based building materials. These materials exhibit impressive properties, including thermal insulation [2], acoustic absorption [3], fire resistance [4] and low embodied carbon [5]. Thus, they might hold the potential to mitigate approximately 40% of global emissions arising from construction and building operations [6]. MBC, known for their biodegradable properties, are effective alternatives to high-embodied insulation materials like expanded polystyrene (EPS), which takes about 500 years to decompose in landfills. The bio-fabrication of MBC entails the careful cultivation of mycelia within lignocellulose substrates that have been precisely shaped using molds. Following this growth phase, a heat treatment is applied to effectively halt any further growth of the mycelia or fruiting body [7], creating a range of products such as biodegradable packaging [8], acoustic panels [9], interior design products [7], and leather alternatives [10]. The mechanical properties of these composites vary based on factors such as fungal species, substrate composition, and growing conditions [2, 8, 11], which opens various avenues for research and development. The structural potential of mycelium, which involves testing various bio-fabrication strategies for building applications and scaling up, has been explored; however, various limitations have been identified [12], such as low mechanical strength and hydrophilic properties, which restricted construction applications.

This study explored the bio-fabrication potential of underutilised Australian agricultural and industrial biomass waste, such as bagasse, hemp hurd, mulch, and sawdust, for bio-fabricating MBC. Most studies which used the Reishi fungus used the *Ganoderma lucidum* species for the MBC bio-fabrication [10, 2, 13]. This study serves as one of the initial investigations into the Australian Reishi fungus (*Ganoderma steyaertanum*) for bio-fabricating MBC with local biomass waste obtained from its source. We used volume and weight measurements, compressive strength testing, and scanning electron microscopy (SEM) imaging for assessment.

2 Methodology

2.1 Materials

Five types of industrial and agricultural biomass waste were selected for this study as substrates, including sugarcane bagasse, mulch, hemp hurd, and sawdust. These were chosen based on their regional availability, cellulose and lignin content, and current disposal practices. The sugarcane bagasse was provided by Sunshine Sugar (https://www.sunshinesugar.com.au/) in Ballina, New South Wales. The mulch was collected from a golf course in Sydney. For hemp hurd, we purchased it from Rootlab, an Australian mushroom supplies store in Sydney. The sawdust was sourced from Mighty Kitchens, a furniture design and manufacturing company in Sydney. Australian Reishi fungus (*Ganoderma steyaertanum*), a locally available fungal species known for its robust mycelial growth, was used as the bio-fabricator in all experimental conditions. The fungus grain spawns were purchased from 'Little Acre Mushrooms' in Australia (https://littleacre.com.au/).

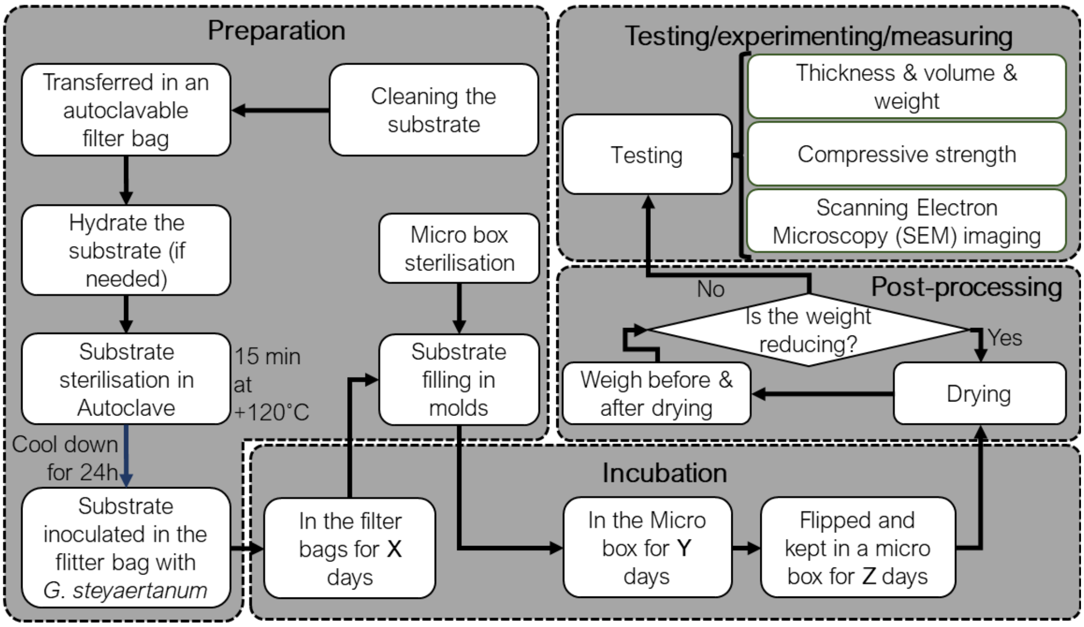
2.2 Methods

Bio-fabrication of MBC samples: The MBC samples were bio-fabricated with four steps: preparation, incubation, post-processing, and testing (Figure 1A).

- **Preparation:** Each type of biomass waste substrate (bagasse, mulch, hemp hurd, and sawdust) was placed into separate large autoclavable filter bags for preparation. The substrates (~2 kg) were hydrated with distilled water (200 g), equivalent to 10% of the substrate's dry weight. The filter bags were sealed with masking tape, making it easier to open the bags at later stages. Then, the filter bags were placed in an autoclave for 15 minutes at 121°C to sterilise the substrate. After that, the substrates were left to cool down for 24 hours. The fume hood table was always sterilised with 70% Ethanol before starting from this stage to reduce the chance of contamination. After 24 hours, the autoclaved filter bags were opened under the fume hood to maintain a sterile environment for inoculating the substrate with 200g (Total 10% of the 2 kg substrate dry weight) *Ganoderma steyaertanum* grain spawn.
- **Incubation:** After inoculating the substrates, the filter bags were sealed with masking tape and placed in a Climatron (dark growth chamber) at 24°C and 70% relative humidity. The inoculated filter bags were massaged daily for seven days to break up the clustered fungal colonies and spread them throughout the bag. After seven days, the substrates were placed in custom-made mold trays with dimensions of 43 mm (length) × 43 mm (width) × 43 mm (height). Each tray could accommodate nine samples. The molds were designed and made to fit inside the Micro box with filtered lids. The closed micro box with sample mold trays was placed in the growth chamber for seven uninterrupted days. After seven days, the samples were flipped to provide better access to oxygen for mycelium growth on all surfaces. The flipped samples were then placed in the Climatron for an additional five days.

- **Post-processing:** After a total of 12 days of molding and incubation, all samples were dried in an oven at 80°c for approximately 8 hours to prevent further mycelial growth during the post-processing stage. The final samples were about 40 mm × 40 mm × 40 mm in size.

(A)



(B)

Figure 1(A) Methodology of bio-fabricating MBC samples; (B) MBC samples bio-fabricated with different substrates, where the first row is bagasse-based, the second row is Mulch-based, the third row is hemp-based, and the final row is sawdust-based MBC samples.

The only difference was the sawdust-based MBCs. There were no visible mycelium colonies after one month of incubation, and the sawdust was very granular and dry. Therefore, we added 200g more water after one month. The initial incubation of the sawdust in a large filter bag took place over a period of two months, during which we observed visible mycelium colonies. Then, the inoculated sawdust was molded and incubated for another 15 days before we flipped them. After another 5 days, we dried the MBC samples with sawdust. Five samples of each of the five types of substrates based on MBC were used for testing (Figure 1B).

Compressive strength testing: The compressive properties of the MBC samples were evaluated according to the ASTM D1621-00 standard [14], specifically designed for rigid cellular materials. Five samples of each substrate type were used (Figure 1B). Cubic specimens with nominal dimensions of 40 mm × 40 mm × 40 mm were used, ensuring that all faces were parallel and perpendicular to the loading direction to prevent uneven stress distribution. Before testing, the samples were conditioned at 23 ± 2 °C and 50 ± 5% relative humidity for 48 hours to stabilise moisture content and internal structure. Compression testing was performed using a Shimadzu AGS-X testing machine equipped with flat, rigid plates. The crosshead speed was set to produce a nominal strain rate of approximately 10% (4 mm/min), in line with the standard's recommendations for cellular materials.

During the test, a compressive load was applied until either 10% strain was reached or visible structural failure occurred. The compressive strength was calculated as the maximum load divided by the initial cross-sectional area of each specimen. Load and displacement data were recorded continuously to generate stress–strain curves, from which the elastic modulus, proportional-limit stress, and plateau stress (if present) were derived. Three replicates were tested to account for variability inherent in bio-based materials. All testing conditions, specimen dimensions, and any deviations from ASTM D1621-00 were thoroughly documented to ensure the traceability and repeatability of the results.

The stress-strain behaviour of four different lignocellulosic materials (Bagasse, Sawdust, Mulch, and Hemp) was investigated through uniaxial compression testing. Cube samples of each material, with nominal dimensions of 40 mm in width, 40 mm in length, and 40 mm in height, were subjected to a compressive force until failure. The raw data, consisting of time, force, and stroke measurements, were extracted from a CSV file. For each sample, the engineering stress (σ) and engineering strain (ϵ) were calculated using the following equations:

$$\sigma = \frac{F}{A_0} \tag{1}$$

where F is the measured compressive force and A_0 is the initial cross-sectional area of the sample, calculated as the product of the initial width and length.

$$\epsilon = \frac{\Delta L}{L_0} = \frac{L_i - L_0}{L_0} = \frac{Stroke}{H_0} \tag{2}$$

where ΔL is the change in length (equal to the stroke of the testing apparatus), L_i is the instantaneous length, and L_0 is the initial height (H_0) of the sample.

Stress-strain diagrams were generated by plotting the calculated engineering stress (MPa) on the y-axis against the engineering strain (%) on the x-axis for each combined plot of all substrate classes (MBC) together. To visually distinguish between material types in the combined plot, different line styles were used for each substrate class (Figure 2).

Scanning Electron Microscopy (SEM) imaging: A field-emission scanning electron microscope (Zeiss Supra 55VP) was used to examine the mycelium and its interface with the substrate. This instrument employs a field-emission gun (FEG) as the electron source, providing a finely focused and stable electron beam that enables detailed visualisation of micro- and nanoscale surface features. Before imaging, samples were sputter-coated with a thin layer of chromium to enhance electrical conductivity and minimise charging effects under the electron beam. Imaging was performed under high-vacuum conditions at accelerating voltages ranging from 3 to 5 kV, with working distances and magnifications optimised to capture both surface topology and the structural interface between the mycelium and substrate. The acquired micrographs facilitated detailed analysis of hyphal network organisation and potential adhesion characteristics at the interface.

3 Results and discussion

The stress-strain diagram (Figure 2) revealed distinct mechanical responses for the four substrate-based MBCs: bagasse, mulch, hemp and sawdust. Significant variations are observed both between the different material types and among the five samples within each group, highlighting the inherent variability in these natural fibre-based composites. Bagasse, mulch, and hemp-based MBC samples had well-covered mycelium skin (Figure 1B). In contrast, sawdust-based samples were brittle and had very little mycelium skin around the samples (Figure 1B) despite having undergone the most extended incubation period.

Mulch-based MBC samples outperformed the others, reaching a peak strength of approximately 0.20 MPa at a strain of roughly 150%, a testament to the dense hyphal mesh and robust interlocking in their heterogeneous wood chip blend. Bagasse composites followed, with ultimate strengths ranging from 0.05 to 0.13 MPa and failure strains between 120% and 150%, reflecting a well-connected yet more ductile network within the fibrous matrix. Hemp-hurd MBC exhibited the greatest scatter, with some samples fracturing below 0.02 MPa at strains under 30%. In comparison, others gradually hardened to approximately 0.15 MPa near 140% strain, underscoring the critical influence of hurd preparation and hyphal colonisation on mechanical consistency. Sawdust composites remain the weakest and most brittle, typically failing below 0.10 MPa and at strains under 100%, a consequence of fine particle compaction and inhibitory formaldehyde/microplastic residues. However, isolated outliers suggest that targeted decontamination and optimised moisture control could enhance their performance.

The varying stress-strain curves highlight the significant impact of the source material (bagasse, mulch, hemp, and sawdust) and processing methods on the final mechanical properties of the composite materials. The considerable intra-group variability, particularly evident in the sawdust and hemp samples, suggests challenges in achieving consistent and homogeneous composite materials using these feedstocks. This variability can be attributed to factors such as the non-uniformity of natural fibres, inconsistencies in matrix bonding, or variations introduced during the composite bio-fabrication process.

The higher ultimate compressive strengths observed in some mulch samples suggest their potential suitability for applications requiring high load-bearing capacity. However, their lower strain at fracture might limit their use in applications where energy absorption or flexibility is crucial. Bagasse composites appear to offer a more balanced combination of strength and ductility, with relatively consistent behaviour across samples. The wide-ranging properties of the sawdust and hemp composites indicate that careful control of the processing, and potentially the selection of specific fibre types or treatments, would be necessary to achieve more predictable and tailored mechanical performance for applications such as construction, packaging, or insulation.

Further investigation into the composition, fibre alignment, density, and processing techniques for each composite type would be beneficial to better understand the factors contributing to the observed variations and to optimise these materials for specific end-use requirements. Additionally, evaluating other mechanical properties such as flexural strength, tensile strength, and impact resistance, as well as durability and thermal properties, would provide a more comprehensive assessment of their suitability for different applications.

SEM imaging (Figure 3) reveals that sugarcane bagasse, mulch, and hemp hurds each provide a highly favourable environment for mycelial colonisation, owing to their fibrous morphology, balanced nutrient profiles, and optimal moisture retention. The loose, porous structure of bagasse and hemp exposes a large surface area and interstitial voids, allowing hyphal strands to penetrate deeply and form cohesive networks around the substrate particles. Likewise, mulch—comprising a mixture of wood chips, leaves, and bark—offers a heterogeneous matrix rich in cellulose and hemicellulose, which fungi readily degrade and use to fuel rapid hyphal expansion. As a result, SEM images of these substrates consistently show thick, multi-directional hyphae enveloping and binding substrates into a dense, interlocking scaffold, indicative of strong mechanical interfacial bonding and a continuous mycelial network.

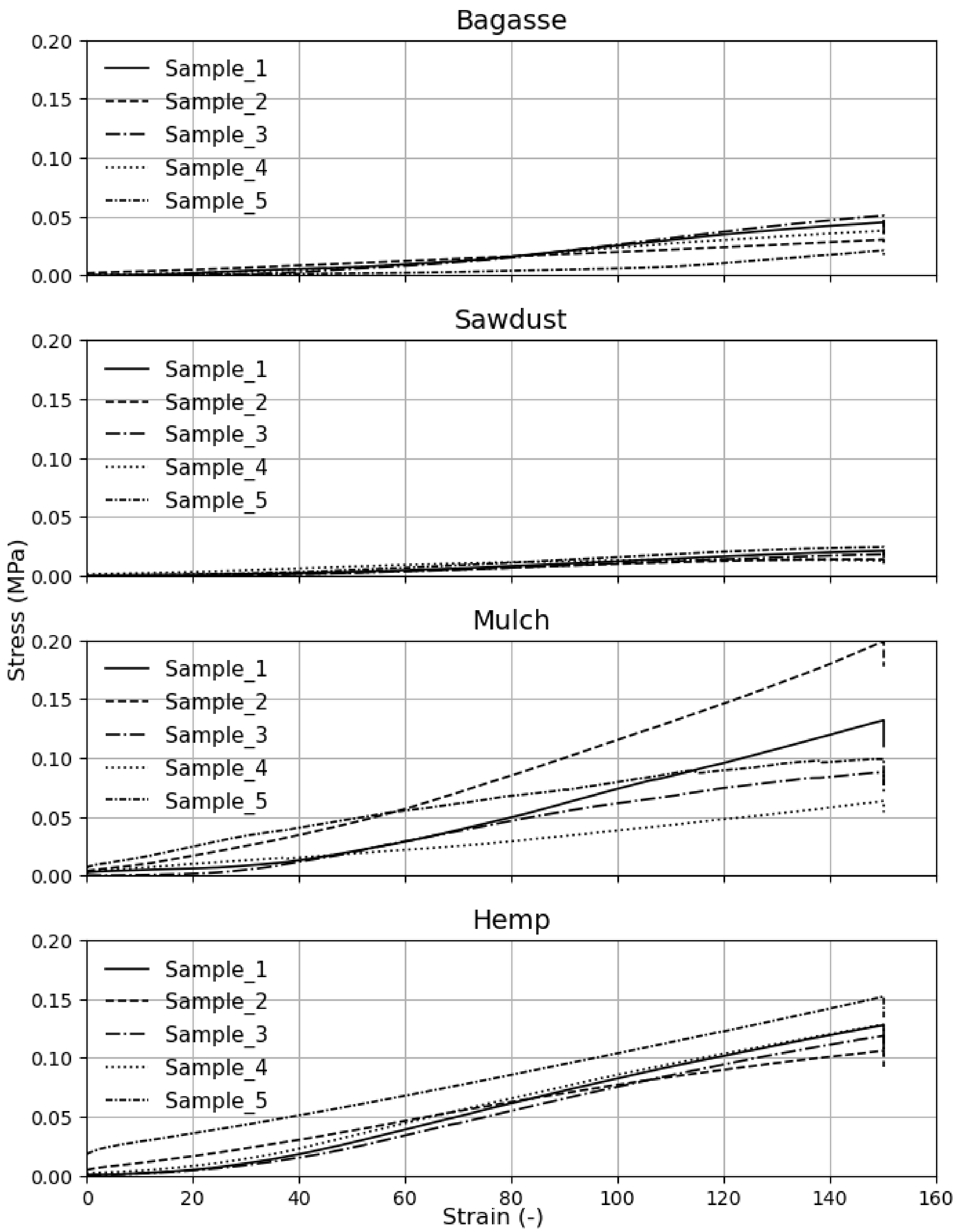


Figure 2: Stress-strain curves for MBC samples fabricated from bagasse, sawdust, mulch and hemp substrates. Each substrate class had five samples.

In contrast, sawdust substrates tended to inhibit robust mycelial growth due to their fine particle size, limited pore space, and relatively high lignin content, which is more resistant to fungal enzymatic breakdown.

Hyphae colonising sawdust often remained confined to the particle surfaces and failed to bridge gaps or fully enmesh the material, leading to sparse, patchy coverage and weak substrate–mycelium adhesion. Furthermore, sawdust beds could compact under moisture, reducing air-filled porosity and creating microenvironments less conducive to hyphal proliferation. Without additional nutrient supplementation or physical pre-treatment to open the particle matrix, sawdust-based composites show markedly lower mycelial density and poorer interfacial integration compared to those grown on bagasse, mulch, or hemp. Also, the collected sawdust was contaminated with microplastics and formaldehyde from the plywood used in furniture-making, as companies in Sydney utilise various boards, including timber, laminated plywood, plywood, Medium Density Fibreboard (MDF), and laminated MDF, for furniture production, which is cut and processed at the exact location. The sawdust is then either repurposed as animal bedding, composted, mulched or sent to a landfill by the owners or third-party contractors. The presence of microplastics and formaldehyde from the plywood may have hindered mycelium growth by making the sawdust difficult to biodegrade.

The four feedstocks each produced mycelium-based composites with distinctly tunable properties rooted in their lignocellulosic makeup. Mulch delivered the densest, strongest panels, reaching peak compressive strengths that suit rigid insulation and load-bearing applications. At the same time, sugarcane bagasse strikes an optimal balance of moderate strength and high ductility, making it ideal for energy-absorbing or acoustic applications. Hemp hurds demonstrated wide mechanical variability, indicating that precise control over hurd size, fungal loading, and incubation is essential to harness their full potential. In stark contrast, sawdust composites proved weak and brittle: fine particle packing, plus residual formaldehyde and microplastics from engineered wood boards, inhibited fungal colonisation and compromised interfacial bonding.

These results underscore the imperative of rigorous feedstock selection and pre-processing. Mulch excels where high stiffness is non-negotiable; bagasse offers versatility for both structural and insulating uses; hemp demands stringent quality control for consistent ductility; and sawdust must undergo targeted decontamination, advanced sorting, or particle-size optimisation before yielding reliable MBC bio-fabrications. Critically, this highlights the need to reform Australia's waste-management policy to mandate the separation of engineered-wood residues, which are laden with microplastics and formaldehyde, from truly biodegradable sawdust, thereby preventing soil pollution and chemical contamination at the source. Systematic refinement of substrate grading, nutrient supplementation, and moisture regimes will further reduce batch-to-batch variation, enabling the production of tailored composites for specific industry needs.

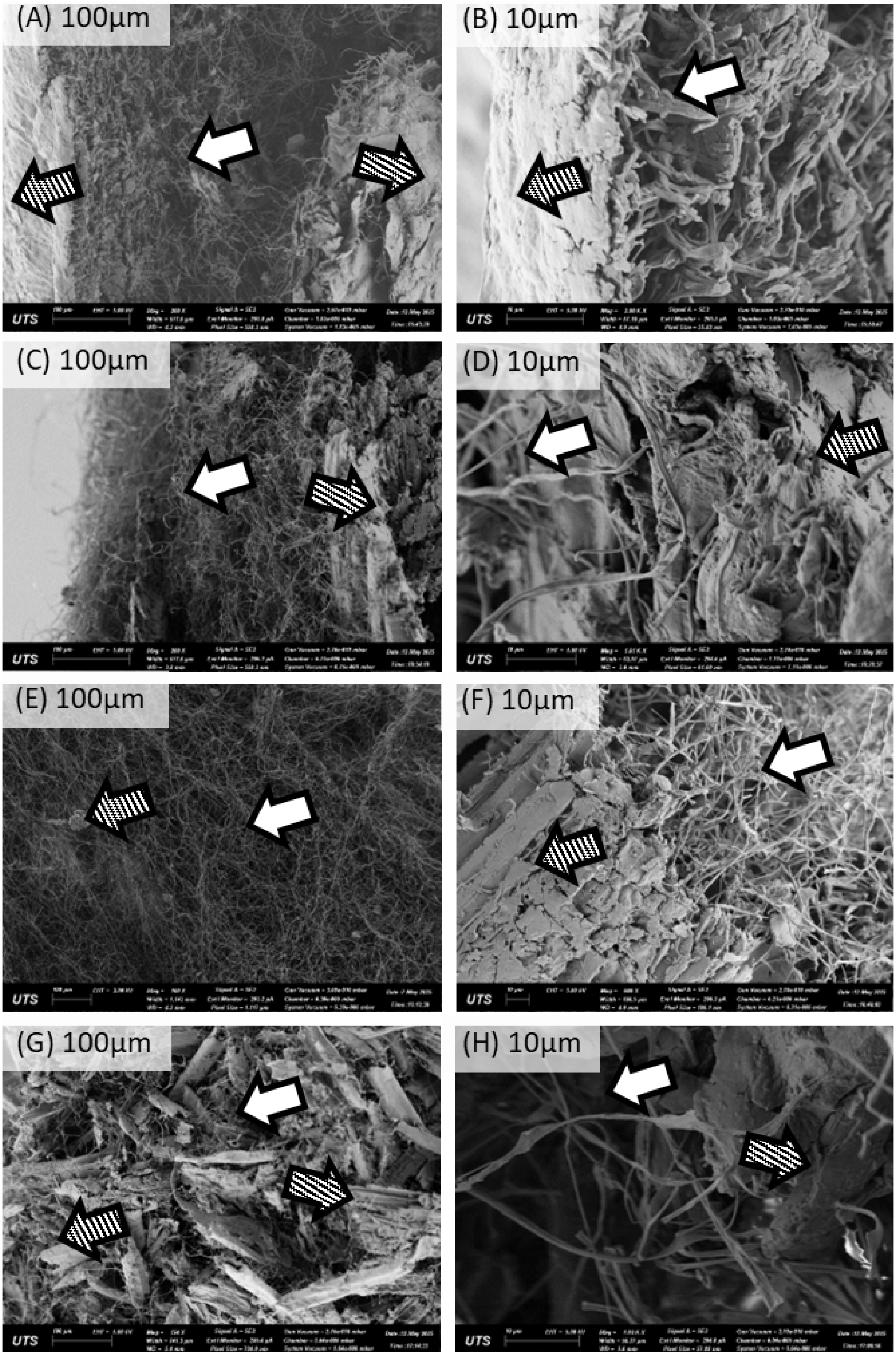


Figure 3: SEM images of mycelium and its interface with the substrate in the MBC samples bio-fabricated with (A, B) Bagasse, (C, D) Mulch, (E, F) Hemp hurd, and (G, H) Sawdust. White arrows are the mycelium, and hatched arrows are the substrates.

Crucially, this work lays a scalable foundation for Australia's circular bioeconomy: diverting millions of tonnes of agricultural residues and clean wood waste from landfill, open burning, and bushfire fuel loads into low-energy, biologically driven fabrication. By valorising mulch, bagasse, hemp, and—once properly sorted—sawdust into high-value building and packaging materials, we can slash greenhouse-gas emissions, mitigate fire hazards, and advance national net-zero targets. Moving forward, integrated life-cycle assessments, small- to large-scale prototyping, and pilot-scale demonstrations will be crucial in translating these lab-scale insights into transformative, low-carbon solutions for Australia's waste management and manufacturing sectors.

4 Conclusions

This research demonstrates the feasibility of converting diverse Australian agricultural and industrial wastes into high-performance mycelium-based composites through a low-energy, biologically driven process using the native Reishi fungus (*Ganoderma steyaertanum*). By integrating volume and weight measurements, compressive strength testing, and SEM imaging, we showed that mulch yields the densest and strongest MBCs for non-load-bearing construction and interior finishes. At the same time, bagasse and hemp hurds produce ductile MBCs that are thermally and acoustically insulating materials. However, sawdust-based composites are impeded by microplastic and formaldehyde contaminants, underscoring the need for targeted decontamination or sorting protocols. Leveraging regionally abundant biomass streams and indigenous fungal species, this work lays a scalable foundation for circular bio-fabrication in Australia, diverting millions of tonnes of waste from landfill and open burning, cutting carbon emissions, and informing both environmental policy and industrial design towards a sustainable, low-carbon construction and manufacturing sector.

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