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Digital twin-optimised repurposing of spent mushroom substrate into circular bio-based composites

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ABSTRACT

The global mushroom industry generates over 60 million tons of spent mushroom substrate (SMS) annually, presenting both an environmental challenge and an opportunity for sustainable material development (Grimm et al., 2018). This research demonstrates an efficient approach to SMS upcycling through the integration of twin-screw extrusion technology and digital twin simulation, producing high-value bio-based insulation materials while advancing circular economy principles (Martín et al., 2023).

Our study establishes a systematic protocol for SMS processing using twin-screw extrusion, optimised through digital twin modelling to achieve precise control over particle size distribution (200-500 µm) and moisture content. The experimental design explored key processing parameters including extrusion temperature (30-120°C) and screw speed (80-200 RPM), with real-time monitoring of pressure, flow rate, and granule uniformity. The digital twin framework enables predictive process optimisation, reducing experimental iterations while ensuring consistent material properties.

Key findings demonstrate that high-temperature processing (120°C) effectively reduces SMS moisture content from 47% to 22-33%, significantly improving material consistency for subsequent board manufacturing. Operating at 200 RPM and 120°C achieved 95% particle size compliance within the target range, crucial for achieving optimal insulation board density (0.2-0.5g/cm³) and thermal conductivity (≤0.05 W/m·K). Notably, medium-speed processing (150 RPM) at 60°C achieved comparable granule uniformity while reducing energy consumption by 20%, highlighting the potential for sustainable scale-up.

The digital twin model integrates real-time process data with stakeholder requirements, enabling dynamic optimisation of production parameters. This approach can facilitate rapid scaling and quality control while minimising resource consumption (Tao et al., 2019). The model's predictive capabilities allow for proactive process adjustments, ensuring consistent material properties and reducing trial costs during industrial implementation.

Commercial validation with industry partners demonstrates significant potential for market adoption. Collaboration with G's Farm showed a 30% reduction in waste disposal costs, while thermal performance testing by the third party validated the insulation boards' compatibility with construction industry standards. Integration with vertical farming systems (IGS) highlights diverse application opportunities.

This research addresses critical gaps in sustainable material manufacturing by establishing a replicable framework for bio-waste valorisation (Le et al., 2023). The developed protocol, supported by digital twin technology, offers a scalable solution for bio-based material manufacturers. Our approach demonstrates how digital innovation can accelerate the transition toward circular material production while meeting commercial performance requirements.

Keywords: Digital Twin, Twin-Screw Extrusion, Spent Mushroom Substrate, Bio-based Insulation, Circular Economy, Sustainable Manufacturing

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