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Recycled Walnut Shell Abrasives as a Sustainable Feedstock for Binder Jetting

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Abstract
Additive manufacturing (AM) opens new possibilities for the valorisation of materials that would otherwise be wasted. Industrially applied walnut shell abrasives, chosen for gentle abrasive cleaning and surface finishing due to their favourable hardness-to-wear ratio, are typically discarded once their sharp edges are worn down. Previous attempts to use walnut shell powder in polymer material extrusion AM (MEX-TRB/P) filaments required high polymer loadings, limiting the effective use of the biogenic fraction and reducing overall sustainability. Binder jetting (BJT) enables walnut shell powders to be used directly without thermoplastic polymer matrices, thereby increasing material usage efficiency.
In this study, walnut shell particles were used as feedstock. After milling and sieving, powders below 180 µm were selected for BJT experiments. Powder flowability, spreadability, packing density, and layer formation were systematically evaluated. Fine (<63 µm) and coarse fractions were blended in varying ratios to assess their effect on printability. Polyvinyl alcohol (PVA) was used as the binder. Particle size distributions were analysed before and after printing to identify optimal blends.
Printability was strongly influenced by particle size distribution. Fractions containing more than 65% of particles below 63 µm exhibited improved spreading behaviour, better layer cohesion, and enabled stable printing without slippage. Optimal performance was achieved with a liquid saturation of 120% and a layer thickness of approximately 90 µm. A balanced mix of fine and coarse fractions facilitated binder penetration and minimised printing defects.
This study demonstrates that recycled walnut shell abrasives can be processed into powders suitable for BJT when appropriate particle size distributions and process parameters are applied. Compared with polymer-based filament processing, BJT utilises walnut shells more efficiently, thereby enhancing the environmental benefits of recycling this by-product for AM.

Binder jetting, recycled walnut shell, particle size distribution, PVA binder, sustainable additive manufacturing

1. Introduction

Additive manufacturing (AM) offers material efficiency, geometric freedom, and compatibility with bio-based or recycled feedstocks. Among AM technologies, Binder Jetting (BJT) is particularly attractive in this regard. As a non-thermal process, BJT deposits a liquid binder onto thin powder layers at room temperature [1,2], enabling processing of temperature-sensitive materials that would degrade under high thermal loads.

Walnut shells, abundant agricultural by-products that are industrially used as blasting abrasives prior to AM, are often discarded after this application. Despite edge erosion, they retain remarkable structural integrity. Their polylobate sclereid cell architecture forms an interlocked 3D network, forcing cracks to propagate through lobes rather than cell boundaries, yielding high tensile strength [4]. This robustness has been exploited in composites such as particle boards and concrete [5,6].

In AM, walnut shell research has mostly focused on Material Extrusion (MEX-TRB/FFF). Mechanical properties are highly sensitive to printing parameters [7], and print consistency remains challenging [8]. MEX-TRB applications face limitations: walnut shell content is typically less than 30 wt% to avoid nozzle clogging; hydrophilic biomass poorly adheres to hydrophobic PLA, requiring surface treatment [9-11]. Achieving balance between tensile strength and dimensional accuracy is difficult [12].

BJT overcomes these issues by eliminating thermoplastics and high temperatures. This study explores repurposing spent walnut shell abrasives as BJT feedstock, optimising particle size distribution (PSD) and powder behaviour to convert this by-product into functional, sustainable AM material.

2. Materials and Methods

2.1. Materials

Recycled walnut shell abrasive (Adsom GmbH, Germany) was used as the primary feedstock. A water-soluble polyvinyl alcohol (PVA) powder (Aurelio, Germany) was selected as the binder for its good compatibility with lignocellulosic powders, low toxicity, and effective water-activated bonding.

2.2. Powder Preparation and Characterization

The spent walnut shell abrasive was milled using an ultra-centrifugal mill (ZM100, Retsch GmbH, Germany) with 250 µm, 500 µm, and 750 µm ring sieves to vary comminution intensity. The milled powders were then classified using a vibratory sieve shaker (AS 450 control, Retsch GmbH, Germany), and only fractions below 180 µm were retained for further study.

Two representative fractions were chosen: a fine fraction (<63 µm) and a coarse fraction (63-180 µm). For BJT trials, the fractions were blended with fine-fraction ratios ranging from 10 to 100 wt%, and a constant 30 wt% of water-soluble PVA was added to prepare the printing feedstock. Previous tests confirmed that PVA addition had negligible influence on powder flowability at room temperature, allowing particle size distribution to remain the dominant factor affecting printability.

Following printing experiments, the particle size distribution (PSD) of the blend yielding the best printability was measured using dynamic image analysis (Camsizer XT, Retsch GmbH, Germany) to verify the optimal ratio and ensure reproducibility.

2.3. BJT Trials

BJT was performed on a Z310 system (Z Corporation, USA) using a water-based solution to activate the PVA. Printability was evaluated based on powder bed stability, layer cohesion, and green part integrity. While a sufficient fraction of fine particles improved interlayer friction and powder bed stability, excessive fines could become airborne during recoater movement, increasing the risk of printhead clogging. Printing parameters were systematically varied, and stable printing was achieved at 120% liquid saturation and approximately 90 µm layer thickness. Cylindrical specimens (Ø 20 mm × 20 mm) were printed at least three times per blend to validate reproducibility.

3. Results and Discussion

Figure 1 shows the particle size distributions (PSD) of recycled walnut shell powders after milling with 250 µm, 500 µm, and 750 µm ring sieves. Milling with the 500 µm and 750 µm sieves was inefficient, yielding less than 50% of particles below 180 µm. In contrast, the 250 µm sieve produced a finer powder, with approximately 90% of particles below 180 µm and around 65% below 63 µm. Consequently, the 250 µm sieve configuration was selected for preparing feedstock for subsequent trials.

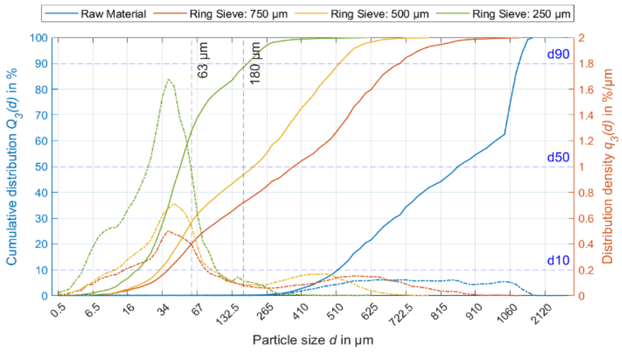

Figure 1. Particle size distributions of recycled walnut shell powders after milling with 250 µm, 500 µm, and 750 µm ring sieves. Dashed lines indicate the particle size thresholds of 63 µm and 180 µm relevant for binder jetting.

Printing trials were then conducted using blends of fine (<63 µm) and coarse (63-180 µm) walnut shell fractions, classified via vibratory sieving (amplitude 1.4 mm, 10 + 10 min). Figure 2 shows the PSD of the optimal blend, formulated with 60 wt% fine fraction. The measured content of particles <63 µm was approximately 65 wt%, slightly higher than expected due to residual fines remaining in the coarse fraction from the high-throughput sieving process.

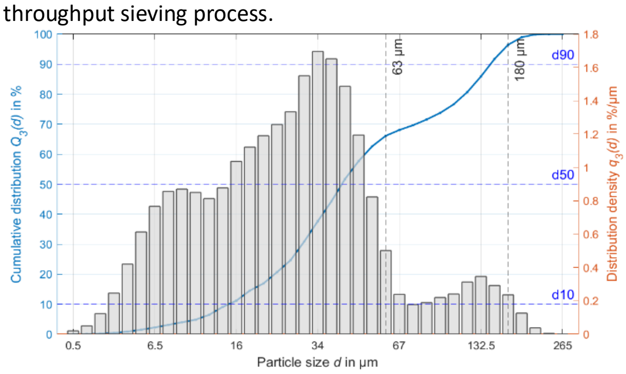

Figure 2. Particle size distribution of the optimised powder blend (60 wt% fine fraction).

Comparison of the PSDs after milling (Figure 1) and after blending and printing trials (Figure 2) highlights the key indicators for optimal printable powders. This suggests that direct milling with a 250 µm sieve could streamline feedstock preparation.

Cylindrical specimens (Ø20 mm × 20 mm) printed under these conditions exhibited excellent shape retention and layer integrity (Figure 3). Reproducibility was confirmed with three repetitions per blend.

Figure 3. Printed cylindrical specimen (Ø 20 mm × 20 mm) from the optimised 60 wt% fine fraction blend.

4. Conclusion and Outlook

This study demonstrated that discarded walnut shell powders can be effectively recycled as a feedstock for BJT, offering a sustainable approach for high-value utilisation in AM. Powders produced with the 250 µm sieve provided the highest usable fraction for printing.

Printing trials confirmed the powders' inherent printability. Blends of fine (<63 µm) and coarse (63-180 µm) fractions achieved stable powder bed spreading and interlayer friction, producing defect-free green parts. The optimal blend contained approximately 65 wt% fine particles, balancing layer stability with minimal risk of printhead clogging. Addition of 30 wt% water-soluble PVA enabled reliable printing without adversely affecting powder flowability, achieving a recycled walnut shell utilisation rate of at least 70 wt%.

The printed parts consist solely of walnut shell powder and water-soluble PVA, making them fully biodegradable and environmentally benign. This demonstrates a practical route to convert biogenic waste into functional materials for AM, highlighting both environmental and process efficiency benefits.

Future work could explore direct milling with a 250 µm sieve, alternative binders, or incorporation of other sustainable biomaterials to further improve printability, material utilisation, and mechanical performance. This study provides a foundation for more circular, resource-efficient AM processes and opens opportunities for expanding sustainable, bio-based feedstocks in industrial 3D printing applications.

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