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Metamateriali sostenibili: progettazione e prototipazione digitale di prodotti di riciclo per costruzioni a impatto zero

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The transition towards Nearly Zero Energy Buildings (NZEB) is a fundamental objective aligned with European Union sustainability goals, necessitating the integration of bio-inspired and fully recyclable materials in lightweight, energy-efficient construction elements. Traditional construction materials often suffer from high embodied energy, with concrete and steel contributing nearly 39% of global CO2 emissions from building operations and construction.
Objectives
To bridge this gap, our work pioneers the use of fully recycled wood-based inks for 3D printing architected metamaterials, providing a sustainable alternative to conventional wood and polymer-based composites. By harnessing the principles of bio-inspiration and additive manufacturing, we achieve over 90% material efficiency with minimal waste, contributing to the advancement of NZEB goals.
Methods
Herein, we present an innovative approach to three-dimensional (3D) printing of bone-inspired metamaterials using a fully recycled wood-based ink. Traditional wood processing methods rely on subtractive manufacturing, leading to material losses of up to 30%. In contrast, our work harnesses a water-based direct ink writing (DIW) technique that reconstitutes waste wood into a printable ink composed of cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs), and lignin—closely mimicking the natural hierarchical structuring of wood. By leveraging this approach, we fabricate architected, damage-tolerant bio-inspired metamaterials with tunable mechanical properties, designed to emulate the multi-scale organization of bone. The metamaterial design is bone-inspired due to bone's unique hierarchical architecture, which provides an optimal balance of strength, toughness, and lightweight characteristics. Bone achieves its remarkable mechanical efficiency through a multi-scale structure composed of a dense outer cortical layer and an inner trabecular network that enhances energy absorption and damage tolerance. Mimicking these features, our printed metamaterials integrate a combination of high-density and porous regions, optimizing mechanical resilience and load-bearing capacity. Furthermore, the alignment of cellulose nanofibrils within the printed structure replicates the anisotropic properties of bone, ensuring enhanced mechanical response under various loading conditions.
Results
Our process involves a combination of freeze-drying and controlled heat treatment to densify the printed structures and enhance their mechanical performance. The printed metamaterials exhibit a compressive strength of up to 31 MPa, and shape fidelity within 95% accuracy assessed via synchrotron imaging. The combination of CNCs and CNFs provides the structural framework, while lignin acts as a natural binder, ensuring the stability and cohesion of the printed parts, as demonstrated via synchrotron-based image-guided failure assessment analyses. In-depth mechanical characterization through image-guided mechanical analysis reveals that the printed metamaterials exhibit enhanced stiffness, toughness, and energy dissipation capabilities compared to conventionally processed wood-based composites. The microstructural analysis using scanning electron microscopy (SEM) and synchrotron imaging further elucidates the internal morphology and crystallinity of the printed structures, confirming their similarity to both natural wood and bone in terms of structural anisotropy and load-bearing capacity. To further ensure structural stability, numerical analyses, including finite element modeling (FEM), are conducted to evaluate load distribution, deformation behavior, and failure mechanisms of the metamaterial designs under various loading conditions.
Conclusion
The ability to 3D print complex, hierarchical architectures with enhanced mechanical resilience and reduced

waste generation offers a promising pathway for next-generation green buildings and bio-inspired engineering solutions. Our findings highlight the potential for bio-based additive manufacturing to transform material utilization in both biomedical and structural applications, reinforcing the critical role of biomimicry in sustainable engineering. This work paves the way for the scalable production of high-performance bio-inspired materials, enabling new possibilities in sustainable design and functional material development.

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