Solvent-mediated molecular engineering of bamboo cellulose towards high-performance biodegradable bioplastics

Jishuai Xu[1] **and Dongdong Ye**[1,*]
[1]School of Materials and Chemistry, Anhui Agricultural University, Hefei 230036, China
*Correspondence: ydd@whu.edu.cn

Received: October 9, 2025; Accepted: November 11, 2025; Published Online: November 17, 2025; https://doi.org/10.59717/j.xinn-mater.2025.100169

Citation: Xu J. and Ye D. (2025). Solvent-mediated molecular engineering of bamboo cellulose towards high-performance biodegradable bioplastics. *The Innovation Materials* **3**:100169.

Global consumption of plastic materials continues to rise, yet their end-of-life management remains a significant environmental challenge. Estimates suggest that around 90% of discarded plastics are either landfilled or enter natural ecosystems, where they progressively fragment into microplastics with potential ecological and human health impacts. This situation has prompted research into materials that combine functional performance with biodegradability and closed-loop recyclability. Cellulose, a renewable and biodegradable biopolymer, offers a potential feedstock for more sustainable plastic production. However, rigid molecular chains and dense hydrogen-bond (H-bond) network make it challenging to melt-process, limiting industrial applicability. Existing production strategies for cellulose-based plastics—including physical dissolving,[1] covalent chemical modification,[2] and dynamic network construction[3]—can improve processability to some extent, but often require high energy input, prolonged processing cycles, and incur elevated costs. In addition, most bioplastics still exhibit lower mechanical strength, reduced thermal stability, and limited processing versatility compared to petrochemical plastics, which constrains their application in sectors such as automotive manufacturing and infrastructure.

FABRICATION OF BM-PLASTICS: MECHANISM AND PERFORMANCE

Bamboo-derived bioplastics have been prepared previously via hot pressing and related techniques,[4] but these approaches often yield materials with high brittleness, low moldability, and limited mechanical robustness. To address both the dissolution of bamboo cellulose and the performance improvement of biomass plastics, Yu et al. proposed a solvent-mediated molecular engineering approach for producing bamboo molecular plastics (BM-plastics).[5] The method comprises two steps (Figure 1A). First, a deep eutectic solvent (DES) composed of $ZnCl_2$ and formic acid is used to disrupt the pre-existing H-bond network within bamboo cellulose, generating a homogeneous molecular dispersion. The DES system is characterized by low toxicity, biodegradability, and relatively simple preparation, and operates under mild conditions without the need for strong alkalis or complex derivatization. Second, ethanol is introduced as a molecular stimulus, promoting the rearrangement of cellulose chains into a more compact configuration. This step enhances H-bond interactions between hydroxyl (-OH) and formate ester (-OCHO) groups. In this context, ethanol acts as a structural directing agent rather than solely as a dehydrating or coagulating medium, influencing the organization of cellulose chains into a denser and more ordered H-bond

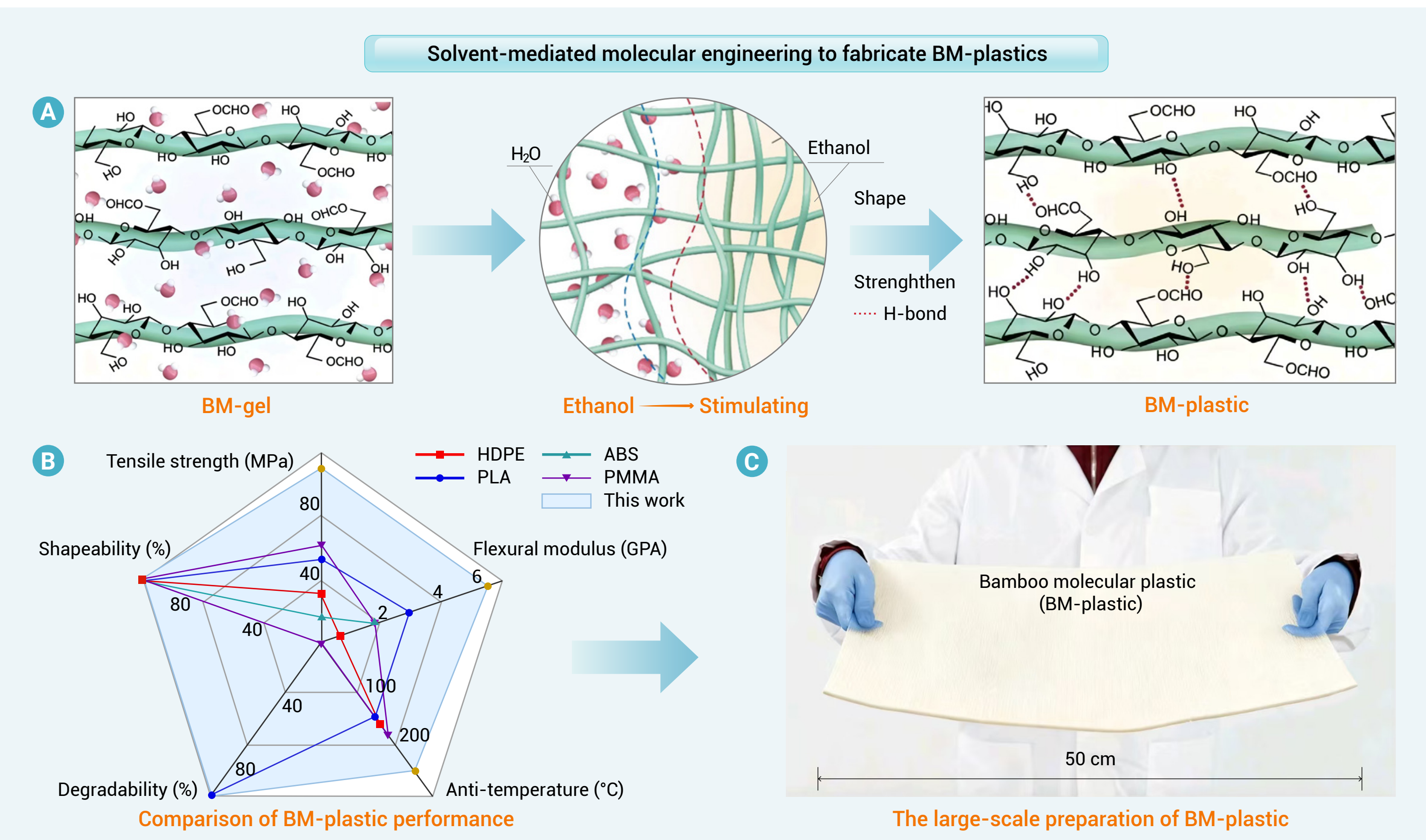

Figure 1. Construction mechanisms, properties, and demonstration of BM-plastic (A) Schematic diagram of the solvent-mediated molecular engineering for BM-plastic fabrication through DES treatment and ethanol stimulation. (B) Comparison of Key Properties between BM-Plastic and Commercial Plastics (HDPE, PLA, ABS, PMMA). (C) Demonstration of the large-scale preparation of BM-plastic.

network. The resulting structure is associated with changes in mechanical and thermal properties.

BM-plastics produced via this method were reported to have a tensile strength of 103.77 MPa and a Young's modulus of 2.24 GPa. They retained structural stability and mechanical integrity under varied temperature (-30 to 100°C) and humidity conditions (70% RH) (Figure 1B). These properties suggest potential applicability in certain industrial contexts where environmental fluctuations are encountered. From an environmental perspective, BM-plastic production incorporates a closed-loop recycling capability. The DES can dissolve BM-plastic waste, regenerating the cellulose molecular system, which is subsequently formed into BM-gel via calcium chloride treatment and reconstructed by ethanol stimulation. In reported tests, recycled BM-plastic maintained approximately 90% of its original mechanical strength. In soil burial experiments, BM-plastic samples were fully biodegraded within 50 days under the tested conditions. This rapid degradation sharply contrasts with the near-zero biodegradation rates of petrochemical plastics and outperforms many bioplastics, such as PLA and PBAT, which degrade only partially under similar conditions. The economic assessment of the process indicates that production costs are competitive with those of several existing bioplastics (Figure 1C). The use of widely available bamboo feedstock and recyclable solvents contributes to cost efficiency. The process can be conducted under ambient conditions, eliminating the need for high-temperature, high-pressure, or high-vacuum steps typically required by many conventional plastic processing methods, which can reduce equipment requirements and energy consumption. Given that bamboo-based biomass plastics exhibit promising properties, they have the potential to replace conventional plastics in several fields, including packaging and daily-use items, industrial and construction applications, and agricultural and forestry sectors.

CHALLENGES, LIMITATIONS, AND FUTURE PROSPECTS

For broader adoption of this solvent-mediated molecular engineering approach, several aspects merit further investigation. Efficient closed-loop recovery of the deep eutectic solvent and ethanol is central to the process economics and environmental footprint; however, maintaining solvent purity during repeated cycles, managing the accumulation of degradation by-products, and ensuring consistent material properties under industrial operating conditions require long-term and scaled-up validation. The intrinsic biodegradability of BM-plastics, with complete degradation in soil observed within 50 days, is advantageous for mitigating environmental persistence. Yet, applications that demand extended service life—such as automotive interiors, building components, or consumer goods subject to variable humidity and temperature—necessitate systematic assessment of long-term mechanical stability, aging behavior, and the influence of cellulose's hydrophilic nature. Beyond technical performance, potential application scenarios for biomass-derived plastics should be evaluated in terms of regulatory compliance, safety standards, and integration into existing manufacturing infrastructure, to clarify market feasibility. Industrial uptake will also depend on the establishment of an integrated supply chain encompassing bamboo cultivation, harvesting, pre-treatment, and centralized BM-plastic production, supported by logistics capable of delivering uniform feedstock quality. Furthermore, the translation from batch laboratory processes to continuous manufacturing systems could be critical for cost reduction and scalability, requiring process intensification strategies and equipment adaptation tailored to solvent-mediated cellulose transformation. Addressing these interconnected challenges—spanning solvent management, durability, application validation, supply chain organization, and process scaling—will be essential in evaluating the practical viability of BM-plastics and positioning them within the broader landscape of sustainable materials development. In summary, this commentary systematically outlines a feasible pathway and provides a solution for mitigating plastic pollution and promoting environmental sustainability.

REFERENCES

1. Zhao H., Hu G.-C., Abraham B., et al. (2025). A sustainable cellulose bioplastic film with extraordinary mechanical performance regenerated by vapor-induced phase separation. *Innov. Mater.* 3:100133. DOI:10.59717/j.xinn-mater.2025.100133
2. Zhou G., Zhang H., Su Z., et al. (2023). A biodegradable, waterproof, and thermally processable cellulosic bioplastic enabled by dynamic covalent modification. *Adv. Mater.* 35:2301398. DOI:10.1002/adma.202301398
3. Ren W., Lin J., Liu Z., et al. (2025). Sustainable, high - performance, aqu - recyclable transparent panels via phase engineering and water - induced plasticization of bamboo. *Adv. Funct. Mater.* Early View:e15830. DOI:10.1002/adfm.202515830
4. Liu C., Luan P., Li Q., et al. (2020). Biodegradable, hygienic, and compostable tableware from hybrid sugarcane and bamboo fibers as plastic alternative. *Matter* 3:2066–2079. DOI:10.1016/j.matt.2020.10.004
5. Tang H., Tong Z., Zhang R., et al. (2025). High-strength, multi-mode processable bamboo molecular bioplastic enabled by solvent-shaping regulation. *Nat. Commun.* 16:8729. DOI:10.1038/s41467-025-63904-2

FUNDING AND ACKNOWLEDGMENTS

The authors acknowledge the financial support from the National Natural Science Foundation of China (52473090), and the Excellent Youth Scientists Fund from the Natural Science Foundation of Anhui Provincial Project (2408085Y025). The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.