Reversible Zein-Based Substrates for Next-Generation Sustainable Flexible Electronics

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Background

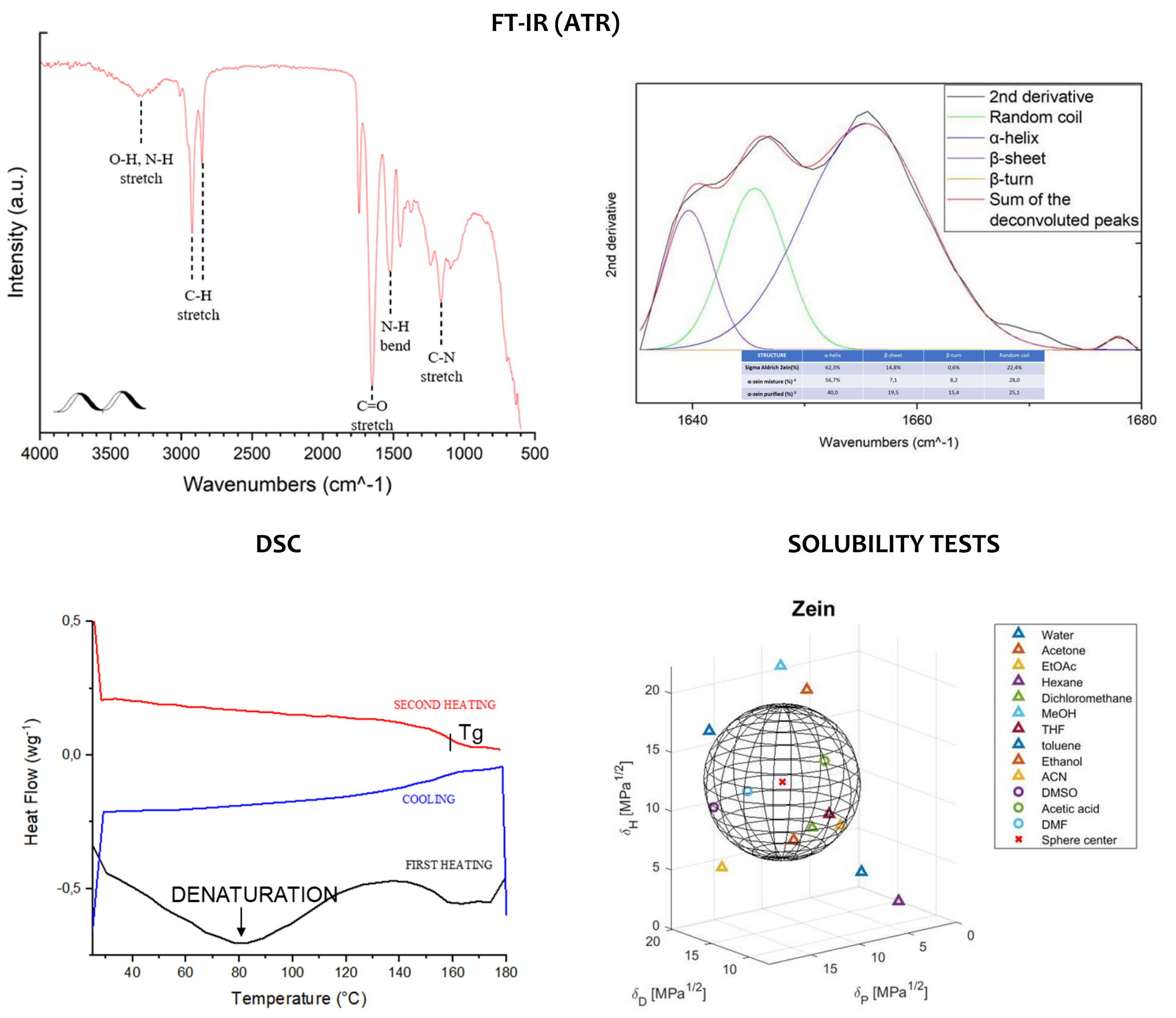
Flexible and hybrid electronics (FHE) are a promising route toward more sustainable devices due to low-energy additive manufacturing and lightweight, flexible materials. However, most current FHE systems still rely on petroleum-based polymers, raising concerns about resource availability, environmental impact, harmful degradation products, and end-of-life disposal [1]. Bio-based and recyclable materials therefore represent a valuable alternative for lower-impact electronics. Here, we present a novel bio-based approach for flexible electronic substrates that uses zein, a protein derived from corn processing waste, as the main polymeric building block. The initial protein was characterised using SDS-PAGE, after which chemical modifications were designed to customise the material properties for electronic applications. In particular, reversible crosslinking via Diels–Alder chemistry was achieved using diene-functionalizedze in and multifunctional maleimide crosslinkers. This strategy has enabled us to develop flexible zein-based materials with tunable mechanical behaviour, with elastic modulus values ranging from 1 to approximately 500 MPa. These materials also demonstrate increased elongation at break of up to 250%, compared with native zein. The resulting materials also exhibited enhanced stiffness, fracture resistance and solvent stability, as well as properties suitable for screen printing. Importantly, the thermoreversible Diels–Alder network enables disassembly at an elevated temperature, facilitating the recovery of soluble protein, solid ink and electronic components through simple filtration.

Objectives

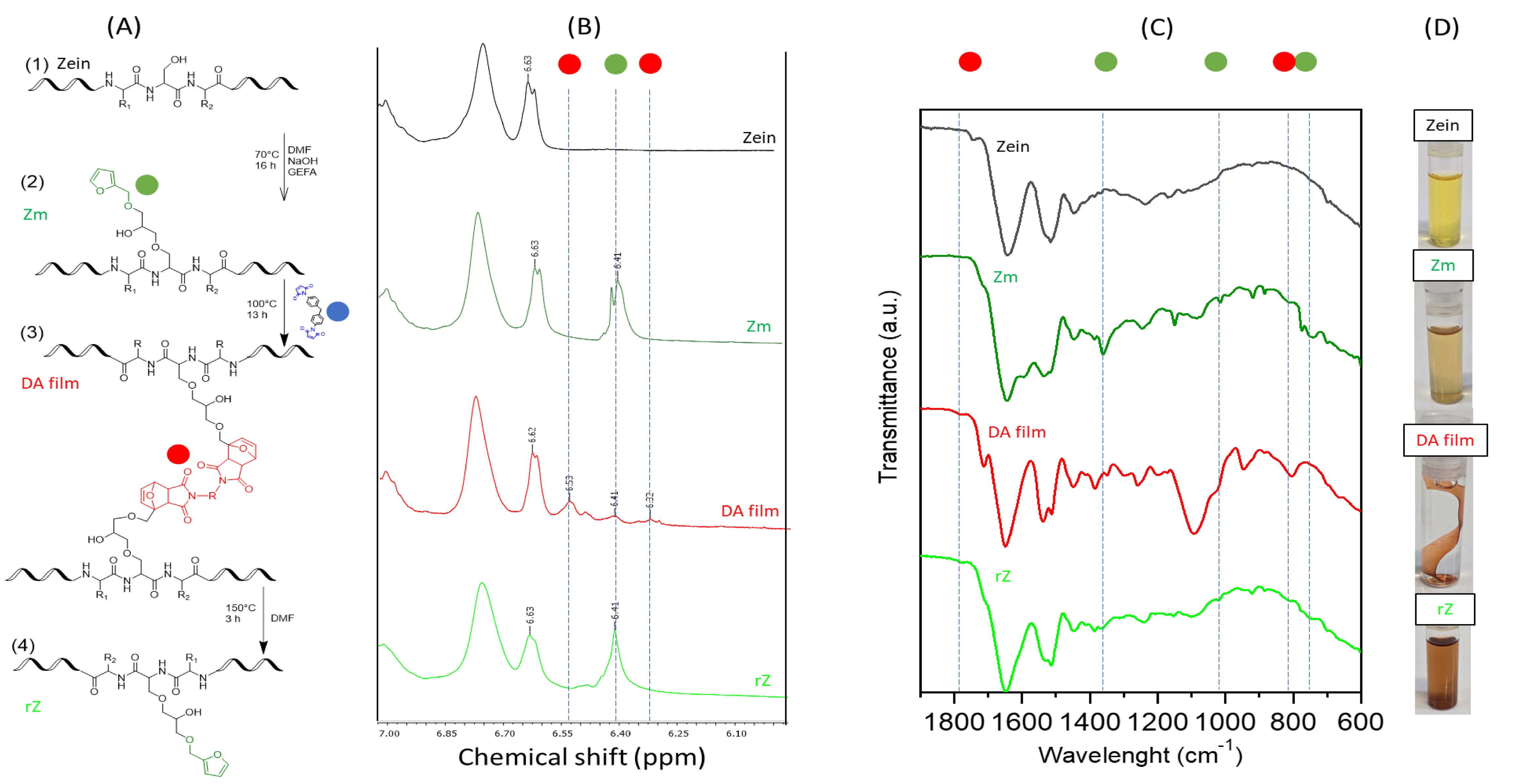
Design and preparation of new bio-based materials for flexible electronics

- Characterization of Zein
- Chemical modification of Zein
- Synthesis of the crosslinkers
- Study of the mechanical and rheological properties of substrates
- Mechanical tests and printing test with conductive inks

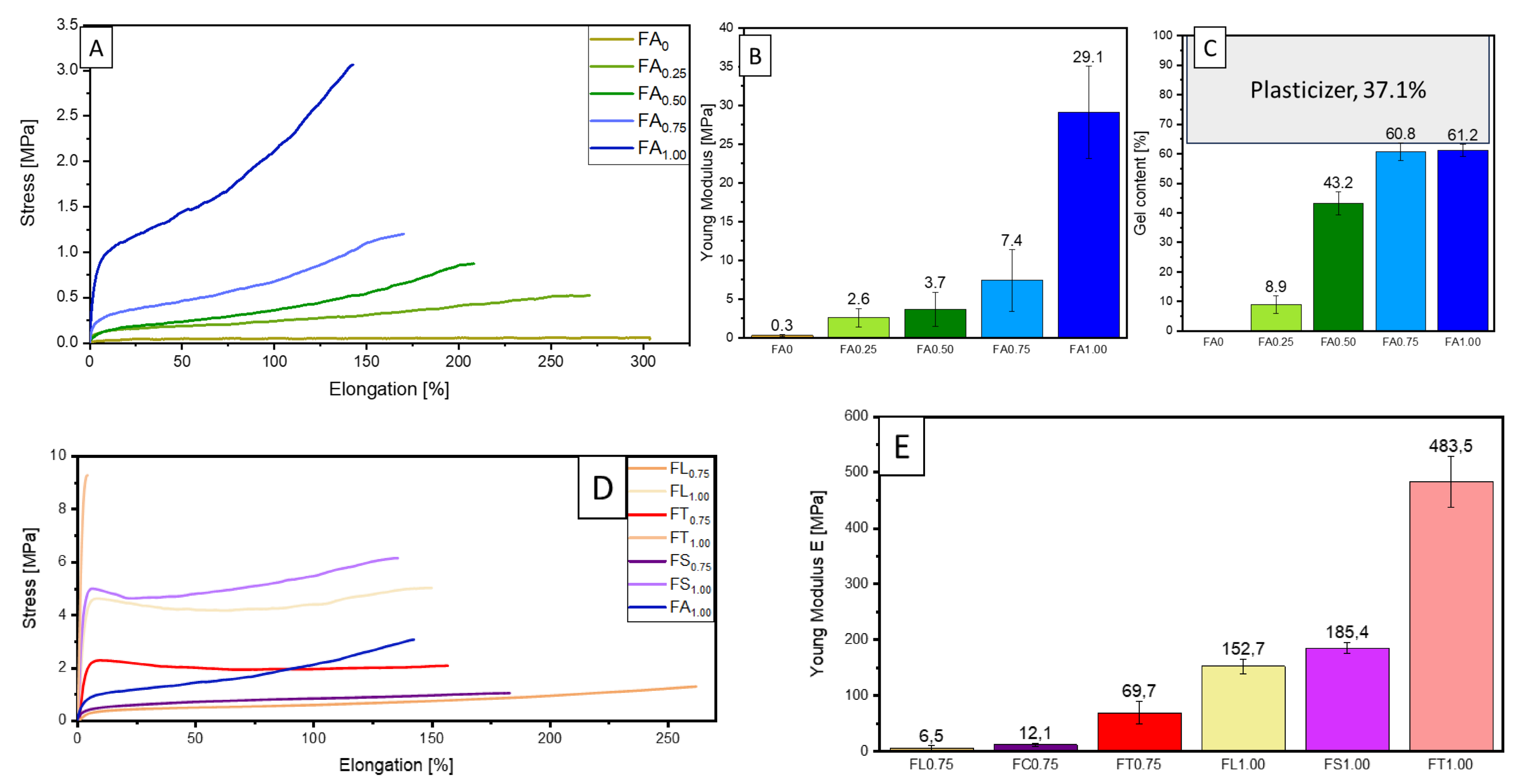
Zein characterization



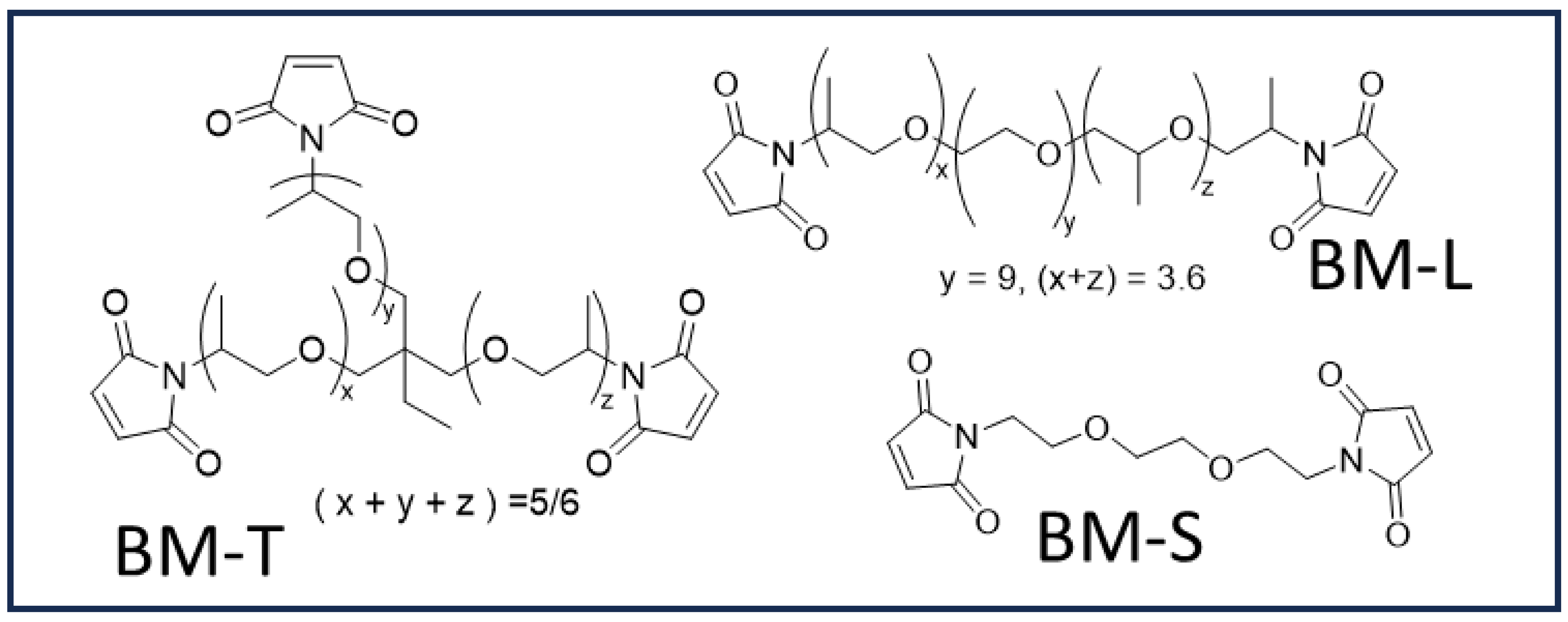
Thermo-reversible film



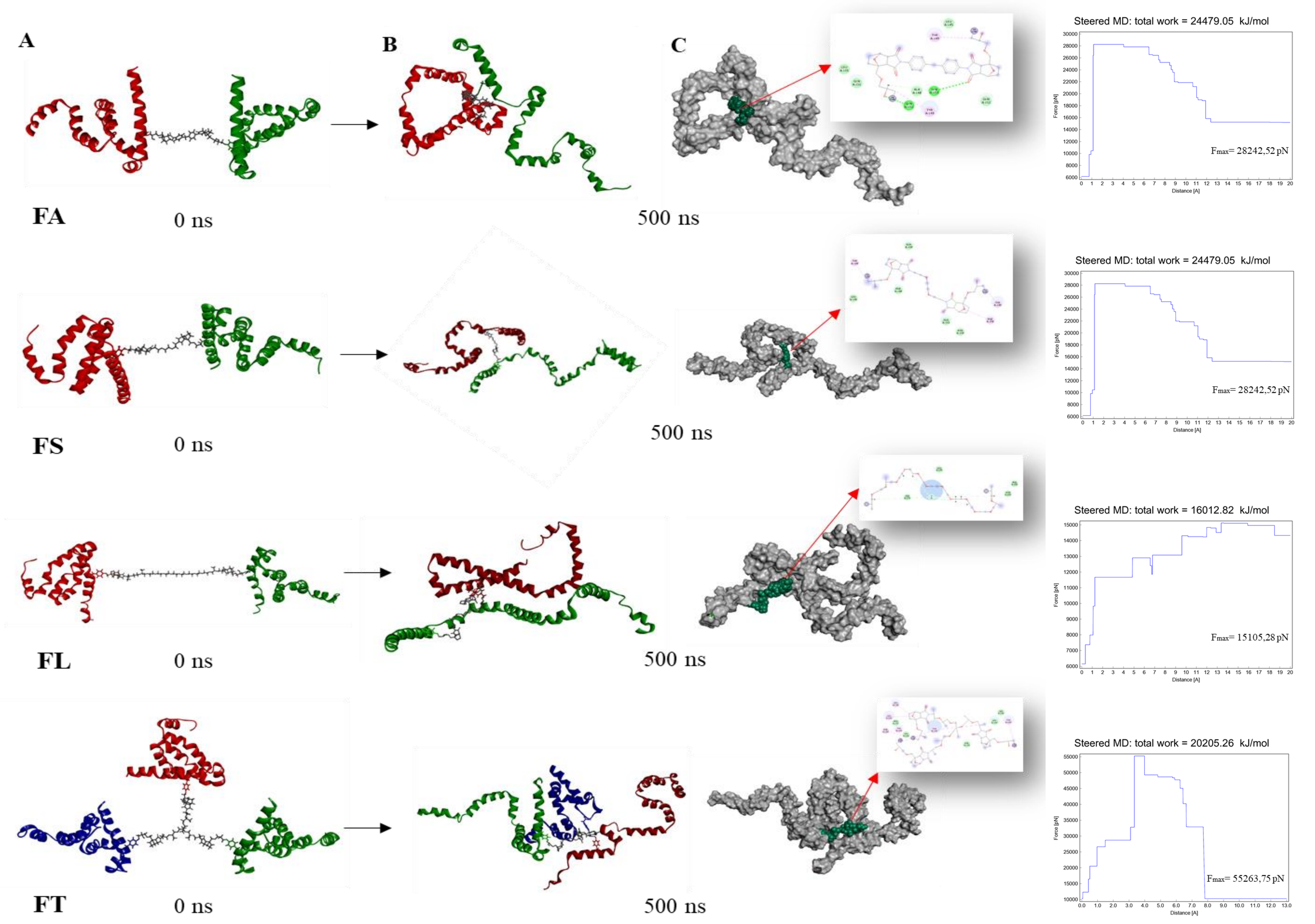
Mechanical performance



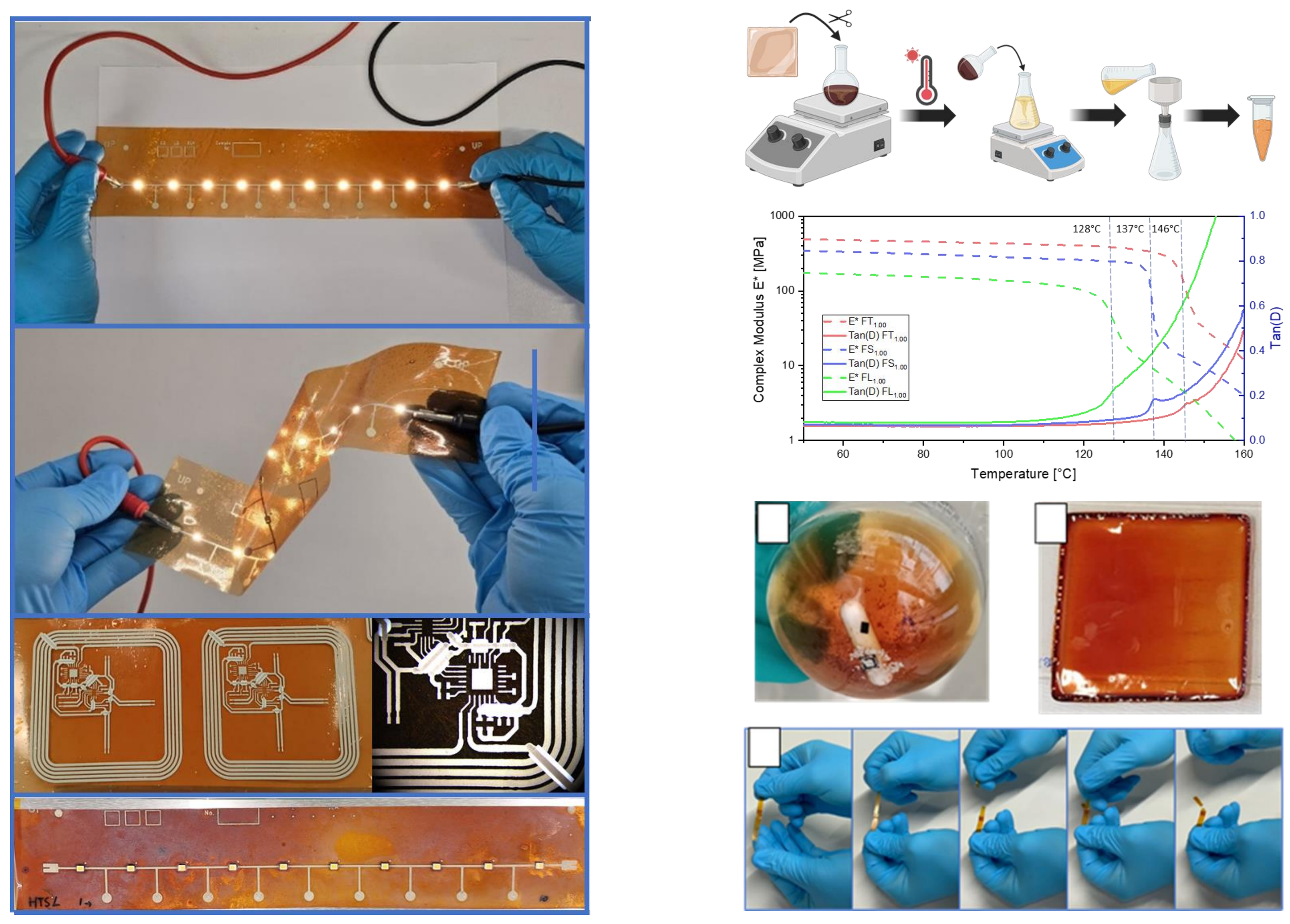
Crosslinker



Computational studies



Printed-device and recycling



Conclusion

This work introduces dynamic protein foils as a sustainable materials platform for closed-loop flexible electronics. Zein, a protein derived from corn processing, was chemically functionalized with furan groups and crosslinked through furan–maleimide Diels–Alder chemistry to form covalent adaptable networks. This strategy produced free-standing, flexible, and processable foils with tunable mechanical properties, ranging from soft deformable films to reinforced substrates with Young's moduli approaching 500 MPa.The optimized zein-based foil was successfully integrated into a printed hybrid electronics workflow, enabling screen printing, conductive patterning, multilayer processing, component assembly, and operation of an LED device. The device remained functional under bending, twisting, and prolonged thermal storage at 110 °C for over 500 hours. Importantly, the thermoreversible network allowed programmed end-of-life disassembly, recovery of functionalized zein with 85% yield, separation of conductive ink and electronic components, and reprocessing into second-generation foils.Overall, the study demonstrates the first protein-derived covalent adaptable substrate for printed flexible electronics that combines mechanical programmability, device validation, repairability, material recovery, and programmed disassembly.

References

[1] D. Gentile, D. Allevi, M. Zambito, L. Criscuolo, M. Galimberti, V. Barbera. Small Science **2026**, 0.

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