

Editor's summary

Wind energy is a key component of the general push to power the world more sustainably. However, modern blades for use in wind turbines are assembled with epoxy resins that are resource intensive to manufacture and cannot be easily recycled. Clarke *et al.* report a polyester material for blade manufacture that can be derived from biomass and straightforwardly deconstructed for recycling at the end of its life by heating in methanol. Performance properties compared favorably to incumbent resins. —Jake S. Yeston

Abstract

Wind energy is helping to decarbonize the electrical grid, but wind blades are not recyclable, and current end-of-life management strategies are not sustainable. To address the material recyclability challenges in sustainable energy infrastructure, we introduce scalable biomass-derivable polyester covalent adaptable networks and corresponding fiber-reinforced composites for recyclable wind blade fabrication. Through experimental and computational studies, including vacuum-assisted resin-transfer molding of a 9-meter wind blade prototype, we demonstrate drop-in technological readiness of this material with existing manufacture techniques, superior properties relative to incumbent materials, and practical end-of-life chemical recyclability. Most notable is the counterintuitive creep suppression, outperforming industry state-of-the-art thermosets despite the dynamic cross-link topology. Overall, this report details the many facets of wind blade manufacture, encompassing chemistry, engineering, safety, mechanical analyses, weathering, and chemical recyclability, enabling a realistic path toward biomass-derivable, recyclable wind blades.

To realize projections of 4 TW global wind energy capacity by 2035 (1, 2), turbines and blades are being constructed at both fast rates and large sizes (3–5). Incumbent epoxy thermosets are favored as the polymer matrix for wind blade fiber-reinforced composites (FRCs), but these materials do not today exhibit practical recyclability (6–8). Although recent epoxy-amine deconstruction chemistries are emerging as a means to recover costly carbon fibers (9–12), these approaches use harsh conditions and are likely impractical for recovering glass fiber at scale (13). Pyrolysis serves as a means of blade waste management, but fiber quality is often reduced by char remnants and loss of surface functionality (14, 15). Down-sizing blade waste (shredding, grinding) for concrete filler also provides a next-life avenue but is ultimately not suitable as a closed-loop solution. Given the dearth of end-of-life solutions, an estimated 43 million tons of wind blade waste is projected to be discarded in landfills globally by 2050 (16).

Dynamic thermosets, namely covalent adaptable networks (CANs) and vitrimers, are emerging as sustainable alternatives to traditional cross-linked polymers (17–19). Montarnal *et al.* first demonstrated zinc acetate-catalyzed in-network transesterification for reprocessable polyester vitrimers (20), a concept proposed in recent FRC designs equipped for end-of-life mechanical recyclability (21–24). Another key advantage of dynamic composites is the topology rearrangement during cure, effectively reducing internal stresses and improving network connectivity that would otherwise compromise performance.

Despite these benefits, industrial adoption of dynamic thermosets is challenged by complicated syntheses, lack of suitable infrastructure for scale-up, and propensity for creep deformation. Overall, new material adoption must consider cost, environmental impacts, manufacturability at scale, and performance while being aligned with the pillars of sustainability. Polyester thermosets from biomass-derivable epoxy-anhydride precursors are promising candidates with supported energy and carbon benefits (25), but these technologies have not been evaluated for large-scale manufacture.

To that end, we demonstrate the manufacturability of biomass-derivable polyester covalent adaptable network (PECAN) FRCs as a sustainable alternative to traditional thermosets, with similar or superior performance in terms of creep, weathering resistance, and thermomechanical performance.

Recyclability

Finally, we evaluated practical end-of-life recyclability of PECAN FRCs (Fig. 5A). Considering that reprocessability has little use in the context of wind blades (40, 41), we placed our immediate focus on chemical deconstruction. To this end, the root component of the 9-m PECAN-15 FRC wind blade was sectioned into 5.0-g cubes for methanolysis at 225°C (Fig. 5C). Preliminary TGA indicated 64.3% fiber mass fraction (35.7% resin) after resin burn-off (Fig. 5D). Initial trials in 75 ml Parr reactors (5 g FRC) identified 6 hours as necessary for suitable deconstruction of the PECAN matrix (Fig. 5B and table S21). Scale-up deconstruction was subsequently conducted in an 8 liter Parr reactor (500 g FRC), where recovered fibers no longer demonstrate a two-step mass loss by TGA and are free from residue as indicated by scanning electron microscopy (SEM) (Fig. 5, C to E). Using 1 wt % 1,8-diazabicyclo[5.4.0]undecane (DBU) as a thermally stable transesterification catalyst returned similar deconstruction results (figs. S50 to S52 and table S21). On the other hand, cubes of RIMR-135 FRC subjected to methanolysis (6 hours) displayed a low (4.2%) overall mass loss (table S21), and TGA and SEM imaging revealed substantial remaining resin content and encapsulated fibers, respectively (fig. S54). Thus, scale-up manufacture and recycling of a 9-m wind blade is accomplished with a performance-advantaged, biomass-derivable resin, further distinguished from epoxy-amine materials.

Further methanolysis (225°C, 6 hours) was carried out on the blade balsa wood component and a PECAN-15 carbon-FRC panel (see methods). Although pristine carbon fiber was recovered (figs. S53), the balsa wood exhibited partial mass loss (table S21). Preliminary separation of the wood may be prudent to avoid product complexity upon downstream recovery. As a demonstration of the recyclable nature of the recovered PECAN FRC products, both recovered glass and carbon fibers were evaluated by single-fiber tension testing, revealing retained fiber σ_B , ϵ_B , and E (Fig. 5F, fig. S55, and tables S22 and S23). Diester and polyol products were also isolated from the deconstruction mixture (fig. S56;

see methods), the former of which has been shown to efficiently convert back to the original methylhexahydrophthalic anhydride (MHHPA) hardener for subsequent PECAN synthesis (25). In an effort to highlight full product reuse, the recovered polyol was applied as a bioderivable and recycled-content linker for synthesizing rigid and elastic polyurethanes (fig. S57; see method), the elastic sample of which demonstrates >200% elongation, suggesting excellent mechanical properties toward sustainable elastomer technologies (Fig. 5H). With these demonstrations, we not only establish an end-of-life management strategy for PECAN blades but propose rational recovery and reuse strategies for each component.

Original article with many charts and graphs available at <https://www.science.org/doi/10.1126/science.adp5395?et rid=40170398&et cid=5335564>