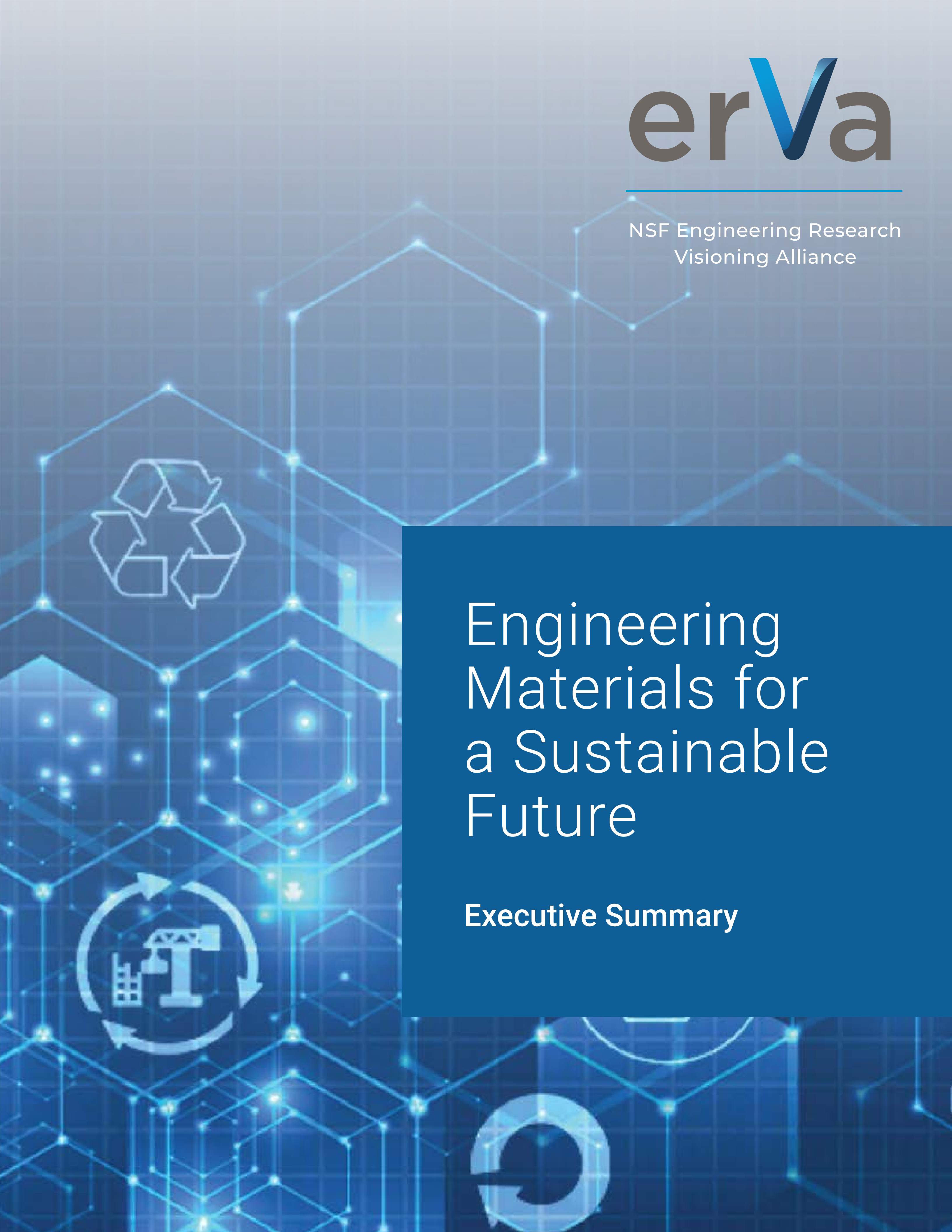

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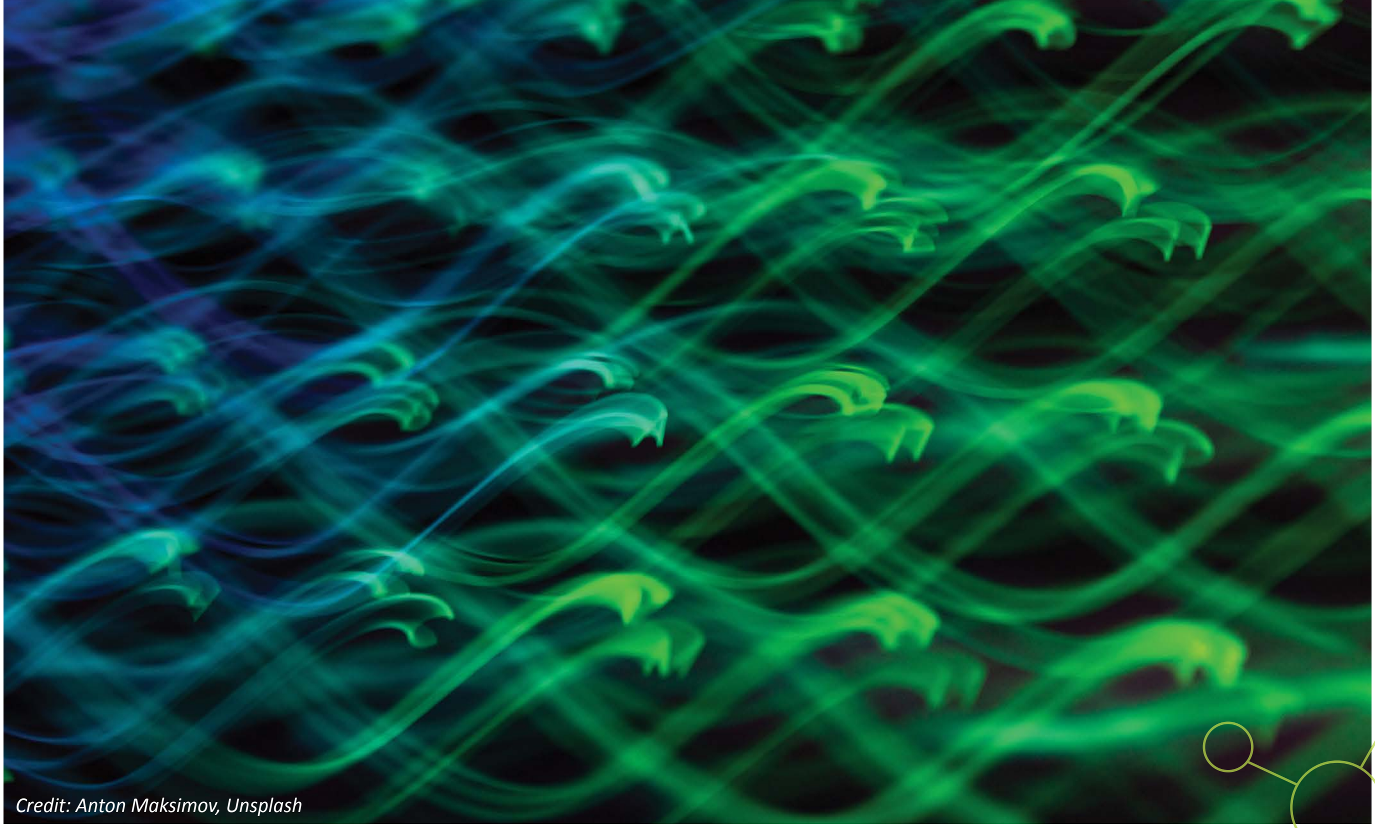
NSF Engineering Research
Visioning Alliance

Engineering Materials for a Sustainable Future

Executive Summary



Credit: Anton Maksimov, Unsplash

Executive Summary

Whether discarding food packaging or traversing a 100-year bridge, all of us experience the impact of materials in daily life. Now is the time for engineering research to rethink the design, scale-up, manufacturing, and end-of-use of materials for the next generation to meet "the needs of the present without compromising the ability of future generations to meet their own needs."[1] If the United States is to achieve a more sustainable society, it will require more sustainable processes and the development (and deployment) of more sustainable materials.

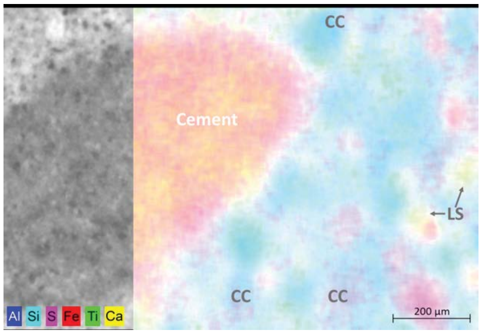
A circular economy is based on three principles: eliminating waste and pollution, circulating products and materials at their highest value levels; and regenerating nature.[2] In 2023, the economy was 7.2% circular, down from 9.1% in 2018.[3] Reversing this downward trend will require reducing material extraction and consumption, enabling design for renewable feedstocks and end-of-use considerations, and transforming current materials to radically increase their sustainability. To achieve a society where we create no new landfills, research across all materials design, use, and end-of-life sectors will be critical.

The global economy must increase its circularity. But material design and discovery takes time; it is not uncommon for it to take a decade or more (and anywhere from $10 to $100 million) to produce a single new material.[4] Additionally, the accumulation of materials in landfills, oceans, and other reservoirs has increased dramatically, requiring transformation to alternative, more sustainable end-of-use formats.[5] Moving toward sustainability and a more circular economy will require extensive changes in critical industries.

> Sustainable material design refers to the development of materials and products that minimize the negative impact on the environment and human health.

Three manufacturing domains that significantly impact sustainability are chemical manufacturing, construction materials, and single-use consumer plastics. Chemical manufacturing comprises about 25% of the U.S. GDP and is critical to creating fuel, fertilizers, plastics, pharmaceuticals, and other essential products.[6] The chemical industry relies on catalytic reactions that operate by burning petroleum fuels at high temperatures, generating significant greenhouse gas emissions and undesirable byproducts. Notably, the materials and processes used in construction, such as steelmaking, globally account for about 3.8% of the U.S. GDP and about 8% of CO_2 emissions, while concrete and cement account for an additional 8% of global CO_2 emissions.[7,8,9] Although these materials are low-cost to produce, most are not easily recyclable. The cement industry alone will need to decrease annual emissions by at least 16% in the next six years to meet the standards of the Paris Agreement.[10] Polymer chemistry provides us with cheap, durable, and customizable multilayer plastic materials for a variety of single-use consumer product packaging, yet these attributes have given rise to massive waste accumulation and contributed to increasing greenhouse gas emissions. Biobased, recyclable, and compostable alternatives to traditional plastics rarely have equivalent functionality to their petroleum-based counterparts. Furthermore, energy-efficient recycling methods for mixed materials waste streams remain an obstacle.

Multidisciplinary engineering researchers can speed the transition to employing more sustainable materials and processes throughout the nation's economy. Creating a long-term roadmap of innovative, less-explored lines of research that can transform all phases of materials' lifespan was the goal of the 55 researchers, industry leaders, policymakers, and other stakeholders at the July 25-26, 2023 visioning event convened by the Engineering Research Visioning Alliance (ERVA). During the two-day event, participants actively discussed grand challenges and identified engineering research priorities spanning materials design, scale-up and manufacturing, and end-of-use scenarios. These are listed below and articulated in more detail in the full report.



Credit: Connor Szeto, Georgia Institute of Technology

Blending of conventional cement with more minimally processed minerals, like limestone (LS) and calcined clay (CC), significantly reduces global warming potential by minimizing the energy- and GHG-intensive clinker fraction. Here, an LS-CC-cement blend was designed to minimize initial porosity by optimizing particle packing density of the unhydrated phases and was imaged by micro X-ray fluorescence spectroscopy (MicroXRF) at 100x magnification. Through the superposition of the individual elemental maps (shown in the color blocks for aluminum, silicon, sulfur, iron, titanium, and calcium), the constituent minerals (i.e., cement, calcined clay, limestone) of the blend are distinguishable within the matrix based on their chemical composition. When reinforced with polymeric fibers, engineered cementitious composites with this composition can exhibit ductility of nearly three orders of magnitude greater than conventional concrete, along with impermeability, crack resistance, and self-healing capacity that contributes to enhanced durability.

Grand Challenges

Design

- Develop multi-scale, multi-property predictive models and simulations coupling atomistic-to-continuum structure property-function relationships that enable the design of more sustainable materials for biodegradability, mechanical properties, electronic properties, dynamic transport, and chemical properties.
- Design new reactors and reactor configurations to handle new feedstocks and low-temperature transformations.
- Design efficient hybrid biological/chemical catalytic transformations for chemical production.
- Develop a fundamental understanding of how to use biological materials and processes and/or waste, including CO2, to fabricate and assemble regenerative matter autonomously into desirable structures and then disassemble these structures by design.
- Develop sustainable engineered materials for improved and operational construction performance.

Scale-up and Manufacturing

- Convert captured CO_2 to useful, high-value chemicals or materials, while assuring that the energy used to drive conversion does not create more CO2 than is converted.
- Develop performance-based mixture proportioning approaches for concrete that can incorporate materials, chemistry, carbon footprint, cost, and durability.
- Develop engineering technologies to reduce the cost of industrial biotech unit operations.
- Conduct chemical separations research (e.g., water from biosystems, sugar extraction, CO_2 extraction) to create more energy-efficient separations technologies.

End-of-Use and Reuse

- Design monomaterial alternatives to multi-layer, single-use consumer goods packaging for an improved end-of-life scenario that still meets performance specifications.
- Create and/or identify enzymes or microbes to selectively and efficiently decompose materials (e.g., microplastics, concrete, etc.) that can be incorporated safely into construction and consumer industries.
- Design new materials for end-of-use recyclability and biodegradability while preserving performance during use.
- Research less expensive and more effective sorting practices at material recovery facilities (MRFs) that can be widely incorporated into these facilities, reducing the need for humans to sort.
- Develop computational methods to predict the biodegradability of new polymers with minimal experimental data – without long-term experimental testing.

Taking Action

Materials influence nearly every aspect of our daily lives. While progress continues in many sectors of materials research, the accelerating rate of climate change and depletion of finite resources mandates a renewed urgency to create more options for sustainable materials in construction, chemicals, and packaging. The following overarching foci should generate essential innovation necessary for the United States to create a more sustainable materials environment.

Predictive Models/Simulations

As in many areas, the use of artificial intelligence (AI) in materials science is not new, but transforming AI’s potential into meaningful impact requires collaboration between materials engineers and AI experts. Priorities for such work include developing systems incorporating physical modeling with machine learning (ML) to generate multi-scale, multi-property predictive models and simulations encompassing atomistic-to-continuum structure property-function relationships. These models and simulations could assist in designing materials for recyclability and biodegradability while evaluating their mechanical, electronic, and chemical properties. Such systems should predict biodegradability of new polymers without long-term experimental testing in wet labs. Additionally, every facet of the circular economy should be considered and addressed in these models to ensure the desired sustainability outcomes.

Facilities

The development of new materials will have limited impact unless these can be produced and adopted at scale. Reconstructing current facilities, designing new reactors and reactor configurations to handle new feedstocks and low-temperature transformations, and enabling triggered disassembly processes at the end of life, will be essential to scale production. Research into scalable hybrid biological/chemical catalytic transformations to develop “traceless” chemicals (high-performing but benign substances) is also essential. While challenges to recycling posed by mixed material streams have been documented, leveraging AI and novel sensing technologies to achieve improved material characterization data in material recovery facilities would assist in creating purer, higher-value waste streams, which incentivizes material recovery facilities (MRFs) to adopt the technology.


Credit: Pixabay

Example of a hybrid sorbent made with a synthetic resin soaked in a copper chloride solution.

Biological Processes/Materials

Research into biological processes during all phases of a material's lifespan is essential. Continued exploration of drop-ins, bio-replacements, and bio-better materials is needed to determine which best meets consumers' product needs and address sustainability concerns in a variety of situations.[11] Fundamental research must occur to better understand how crop-based feedstocks can be grown at a sufficient scale without cannibalizing crops for food production. Additionally, and preferably, the use of waste as feedstock and additives of biobased alternatives that deliver equivalent functionalities should be a priority. Much is still unknown about fabricating or regenerating materials using, for example, grass as feedstocks through biogenetic or industrial processes. These materials must be produced efficiently at scale to create carbon-neutral products. For example, it is critical that researchers develop and test performance-based mixture proportioning approaches that maintain the durability of key building materials, including concrete, while reducing the chemical impact, overall carbon footprint, and cost to enable broad adoption. Another emerging area of interest is expanding the role of microbes and enzymes in the materials lifespan, either through self-healing to sustain the lifespan or to decompose materials selectively and efficiently at the end of their useful life.[12]

Chemical Processes/Materials

Similarly, engineering research is needed on new chemical processes that leverage novel feedstocks in different ways to create sustainable materials and address environmental concerns. This ranges from carbon capture and utilization to electrochemical reduction and mineralization. While these are not novel topics, they need engineering research to be successfully scaled and commercialized. Leveraging CO_2 emissions from industrial processes as a feedstock for commodity products needs new catalytic processes that are efficient, less energy-intensive, and cost-effective.[13] Electrochemical reduction of CO_2 to CO for a feedstock requires further research to leverage renewable electricity sources to drive these reactions, which can convert CO_2 emissions into useful and potentially marketable products. Mineralization involves CO_2 reacting to form stable carbonates, which not only sequesters carbon but also produces valuable minerals; however, this requires optimization to make it economically viable.

Engineering plays a critical role at all stages of sustainable materials development. Many of the grand engineering priorities discussed in this report would be useful not only for developing new materials but could also be applied for post-processing waste materials by breaking them down into raw components that can be reused—truly leading to more circular materials development.

This report aims to inspire researchers and funders (public, private, and nonprofit) to support and pursue these engineering research priorities and bring breakthrough materials research and development to the forefront of current sustainability efforts.

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Our mission is to identify and develop bold and transformative new engineering research directions and to catalyze the engineering community's pursuit of innovative, high-impact research that benefits society.

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