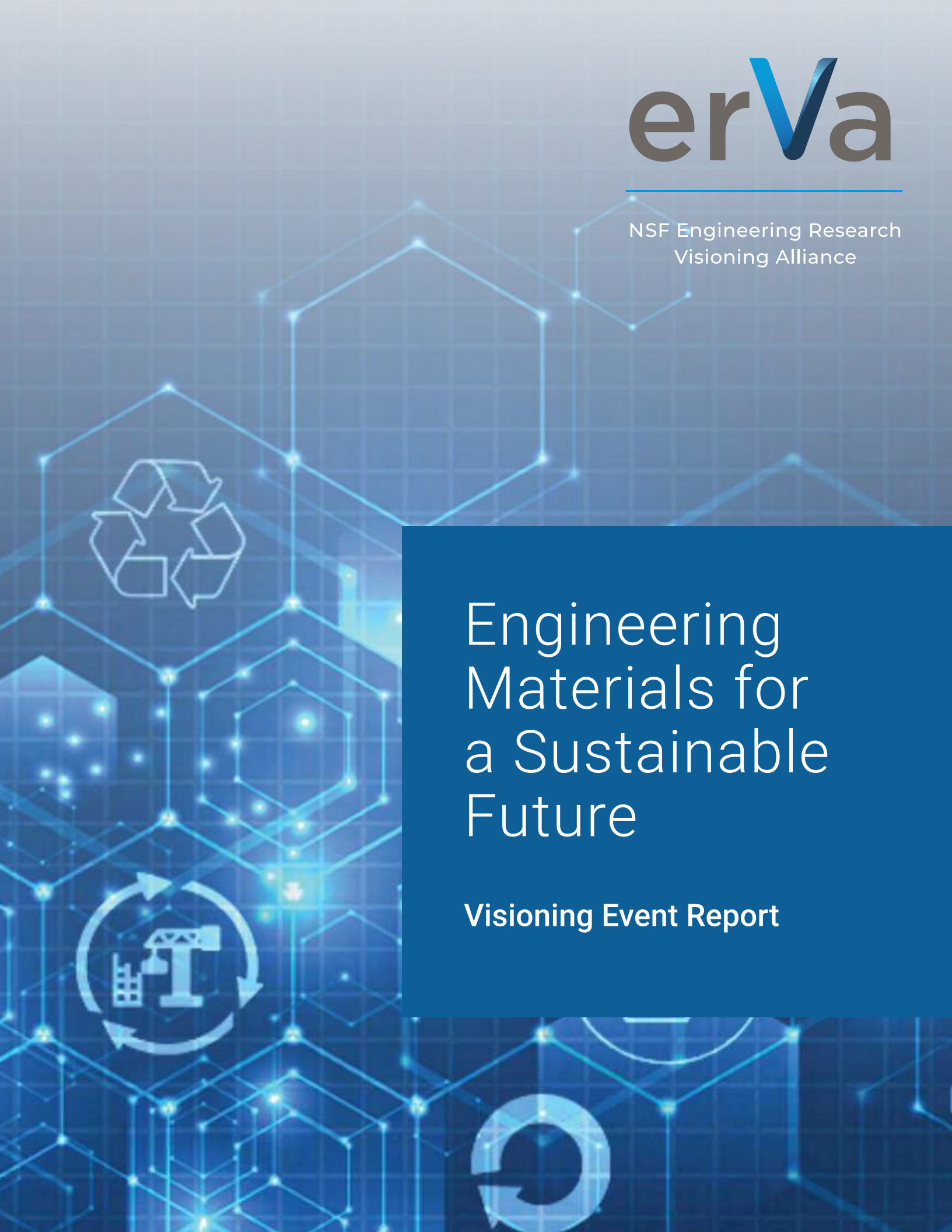




NSF Engineering Research
Visioning Alliance

The background features a blue-toned grid with glowing nodes and lines. Several icons are overlaid: a recycling symbol in the upper left, a circular arrow icon with a factory and crane in the lower left, and a circular arrow icon with a gear in the lower right.

Engineering Materials for a Sustainable Future

Visioning Event Report

Engineering Materials for a Sustainable Future

A visioning report of the Engineering Research Visioning Alliance
Report Finalized February 12, 2024

Based on proceedings from an ERVA event hosted by:



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The Engineering Research Visioning Alliance (ERVA) is a neutral convener that helps identify and develop bold and transformative new engineering research directions, directly supporting the nation’s ability to compete in a rapidly changing global economy. Funded by the National Science Foundation (NSF) Directorate for Engineering, ERVA is a diverse, inclusive, and engaged partnership that enables an array of voices to impact national engineering research priorities. The five-year initiative convenes, catalyzes, and empowers the engineering community to identify nascent opportunities and priorities for engineering-led innovative, high-impact, cross-domain research that addresses national, global, and societal needs. Learn more at ervacommunity.org.

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ERVA visioning events enable the engineering research community to identify nascent opportunities and priorities for engineering-led, innovative, high-impact research that addresses global and societal needs. Each event relies on the efforts of organizations and individuals who volunteer to lead, guide, and participate in its activities.

For program leadership and participant recommendations, gratitude is extended to the event co-host, IBM Research, for providing an inspiring location at its Almaden, CA campus, and IBM's Chandrasekhar "Spike" Narayan, who serves on ERVA's Standing Council, for providing event leadership and recommendations for participants. We are especially grateful to the Thematic Task Force that developed the creative framework for this visioning event and facilitated discussion, led by co-chairs Yael Vodovotz, professor of food science and technology and director of the Center for Advancement of Food Science and Technology at The Ohio State University; and Jennifer Dionne, professor of materials science and engineering, and Chan-Zuckerberg Investigator at Stanford University. Carol Handwerker, Purdue University, and Blake Simmons, Lawrence Berkeley National Laboratory, contributed to planning and development as members of this distinguished group. Also serving on the Thematic Task Force and as event breakout facilitators were Kimberly Kurtis, Georgia Institute of Technology; Laurent Matuana, Michigan State University; Sridevi Narayan-Sarathy, PepsiCo; and Greg Wellman, Eastman Chemical Company. ERVA PI Dorota Grejner-Brzezinska, The Ohio State University, lent expertise and oversight to the event. Special thanks to report writer Susan Lang, director of the Center for the Study and Teaching of Writing at The Ohio State University, for attending the event and writing the report; and facilitation consultant David Glazer, Glazer Design.

This visioning effort benefited from the assistance of annotators Katy Bradford of Georgia Institute of Technology, and Arlene Zhang and Punnag Padhy of Stanford University. ERVA team members Josh Aebischer, Sandy Mau, Annie Shealy, and Rebecca Silveston supported event breakout facilitation, and Natoshia Goines supported event logistics.

Presentations by Ramani Narayan, Michigan State University; Nicholas Rorrer, National Renewable Energy Laboratory; Anish Tilak, Rocky Mountain Institute; and Sabbie Miller, University of California, Davis, informed the event.

Participants from diverse contexts contributed to the event, representing large companies and startups, academic researchers, and government program officers. ERVA is grateful to all the workshop participants who contributed their time to create a valuable discussion and visioning report and to their organizations for the liberty to share their expertise for this effort.

Rebecca Silveston, ERVA executive director, led the event planning, program development, and execution. The event and report development were executed under the guidance of ERVA Principal Investigator Dorota Grejner-Brzezinska, The Ohio State University, and ERVA co-principal investigators Anthony Boccanfuso, UIDP; Charles Johnson-Bey, Booz Allen Hamilton; Pramod Khargonekar, University of California, Irvine; and Edl Schamiloglu, University of New Mexico. Development of the visioning session theme was informed by input from the ERVA Standing Council, Advisory Board, and NSF Directorate for Engineering collaborators.



ERVA visioning event participants, July 25, 2023



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.

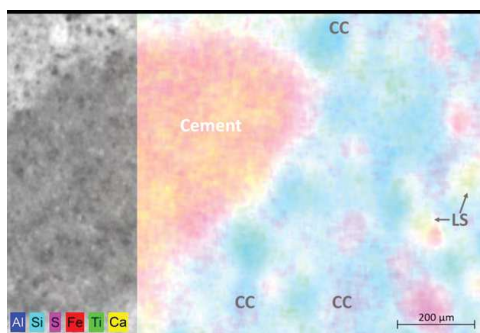
The global economy must increase its circularity. But material design and discovery takes time; it is not uncommon for it to take a decade or more (and anywhere from \$10 to \$100 million) to produce a single new material.⁴ Additionally, the accumulation of materials in landfills, oceans, and other reservoirs 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.

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

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

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 CO₂ emissions, while concrete and cement account for an additional 8% of global CO₂ 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

01

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.

02

Scale-up and Manufacturing

- Convert captured CO₂ 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, CO₂ extraction) to create more energy-efficient separations technologies.

03

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.



Credit: Pixabay

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

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.

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 CO₂ 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 CO₂ to CO for a feedstock requires further research to leverage renewable electricity sources to drive these reactions, which can convert CO₂ emissions into useful and potentially marketable products. Mineralization involves CO₂ 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.

Engineering Materials for a Sustainable Future

If the United States is to achieve a more sustainable society, it will do so largely through the development and use of more sustainable materials. Key stakeholder groups—consumers, producers, and government—have set sustainability as an important goal. Research examining consumer attitudes and spending during 2017-2022 confirmed that consumers desire more sustainable goods and spend money to support their preferences.¹⁴ Recent government action in the United States, including the [2021 Sustainability Plan](#), has galvanized industries to pursue zero-carbon status. Corporate investors are also increasingly interested in developing sustainable materials solutions to enable a circular economy, even if short-term profits take a temporary hit.¹⁵

A circular economy is based on three principles: eliminating waste and pollution, circulating products and materials at their highest value levels; and regenerating nature.¹⁶ In 2023, the economy was 7.2% circular, down from 9.1% in 2018,¹⁷ and other studies demonstrate year-over-year worsening.¹⁸ 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.¹⁹ Additionally, the accumulation of materials in landfills and other reservoirs has increased dramatically, requiring transformation to alternative, more sustainable end-of-use conformation.²⁰

Moving toward sustainability and a more circular economy will require extensive changes in critical industries. Three manufacturing domains that impact sustainability were identified: chemical manufacturing, construction materials, and single-use consumer plastics. Chemical manufacturing comprises about 40% of the U.S. GDP and is essential to creating fuel, fertilizers, plastics, pharmaceuticals, and other essential product compounds. However, most catalytic reactions burn petroleum fuels at high temperatures, generating significant greenhouse gas emissions and undesirable byproducts. Achieving precision chemistry, where reactions are simultaneously high-yield, product-selective, and free from greenhouse gas emissions, will be critical for a sustainable future.



Credit: Canva

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 CO₂ emissions, while concrete and cement account for an additional 8% of global CO₂ emissions.^{21,22,23} Although these materials are low-cost to produce, most are not easily recyclable. The cement industry alone must decrease annual emissions by at least 16% in the next six years to meet the standards of the Paris Agreement.²⁴ Balancing cost and performance while decarbonizing the processes must be considered in designing construction materials to achieve a zero-carbon future.

Polymer chemistry provides cheap, durable, and customizable multilayer structures for a variety of single-use consumer products, such as packaging. Yet these layers are difficult to separate, preventing

Identification 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).

recycling and giving rise to highly visible waste accumulation while contributing to increasing greenhouse gas emissions. Biobased, recyclable, and compostable alternatives to traditional plastics rarely have equivalent performance to their petroleum-based counterparts. Furthermore, energy-efficient sortation and recycling methods for mixed materials waste streams remain an obstacle.

In these instances, new materials using renewable energy and feedstocks, state-of-the-art chemistry, physics, synthetic biology, and artificial intelligence (AI) are required to enable net-zero or negative greenhouse gas emissions, increased recyclability/composability, and progress toward a fully circular materials economy without sacrificing performance. While the joint United Nations-Ellen MacArthur Foundation Global Commitment has brought together over 500 organizations to work toward a circular economy for plastics, insufficient progress has been made toward goals for 2025, particularly in flexible, rigid, and reusable packaging.²⁵

Materials engineering researchers can speed the transition to employing more sustainable materials and processes throughout the nation's economy. Identification 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 identified and discussed grand challenges for engineering researchers, spanning materials design, scale-up and manufacturing, and end-of-use scenarios. A detailed list of research priorities by time frame is presented in Appendix A.

Identified Grand Challenges

#1

Sustainable Material Design



Credit: Mark Stone, University of Washington

A biopolymer film synthesized by bacteria with applications in replacing polymer films, e.g., for packaging.

Engineering more sustainable alternatives to commonly used materials is imperative. Sustainable material design refers to the development of materials and products that minimize the negative impact on the environment and promote circularity. The use of sustainable materials in all facets of society is critical to address global challenges, including accelerating climate change, resource depletion, and pollution. Materials in the built environment can also be designed to have a longer use phase, potentially reducing the need for replacement and minimizing waste, thereby contributing to a circular economy. A critical component on the road to achieving sustainability is in material design driven by choices, from feedstock to end-of-use, while prioritizing circularity.

Engineering new materials for the construction industry should be a priority focus. It is estimated that in 2017, approximately 75% of the 661 billion tons of raw materials used in the United States were directed to the construction industry.^{26,27} In 2022, cement production in the United States reached over 104 million tons.²⁸ Engineering **new or better concrete that is cost-effective** will require multidisciplinary collaboration to determine the efficacy of both autogenous and autonomous healing, as well as evaluation criteria and economically viable mechanisms for self-healing.²⁹ Development of self-healing concrete, or design of new concrete amenable to self-healing that can be widely adopted, will involve acquiring a better understanding of the causes of concrete failure at the microstructural level.³⁰ Such insight will lead to innovative engineering solutions that may combine other sciences (e.g., biology, chemistry, etc.) to arrive at viable, applicable options. Research into creating **plastic or other waste-based construction materials** is also encouraging, but issues such as determining optimal proportions for use, setting design criteria to include effects of aging, safe sanitation of waste to eliminate toxins/contaminants, and standards for quality assessment must be investigated.³¹ Crucial research gaps also exist in **preparing built**

environments for both mitigation of and adaptation to climate change with regional specificity. To develop more holistic and comprehensive climate change preparedness strategies, cross-sector research is needed among academia and industry professionals in urban planning, property, construction, meteorology, and design.³²

Designing for “green chemistry” is also essential. Current chemical design is predominately linear and relies on fossil-based feedstocks and scarce resources to generate products, and the associated waste may be toxic and accumulate in nature. While those products may perform their intended function, public sentiment is more informed than ever about the waste and potential environmental hazards generated over time, creating more pressure to produce alternatives. As consumer spending behavior prioritizes sustainability over cost and convenience, research to engineer new materials should continue to improve functionality in the traditional sense of performance while intentionally assuring sustainable choices.³³ **Designing new materials must be approached from a systems perspective** that considers the full range of consequences of production, use, and reuse or recycling (also known as a cradle-to-cradle approach). Another area for exploration is **engineering low-temperature, low-energy chemical solutions for separating complex electronic products** to reclaim rare earth and precious metals—so-called “urban mining” of known reserves of critical materials.

We must also develop a **fundamental understanding of how to use biological processes and other types of waste**, including CO₂, as a resource **to fabricate and assemble regenerative matter autonomously into desirable structures and then disassemble these by design.**³⁴ Bio-based plastics from polyhydroxyalkanoate (PHA), polyhydroxybutyrate (PHB), and polylactic acid (PLA) show promise as replacements for petroleum-based plastics such as polyethylene (PE) or polypropylene (PP), but more research is required to achieve performance levels and provide consistent and affordable feedstock to establish these as cost-competitive, viable alternatives.^{35,36} AI-assisted experimental selection could be part of the solution to select microbial strains for PHA production that yield polymers with desired functionality while optimizing parameters such as sterilization and low conversion of carbon substrates, poor growth of microorganisms, and downstream separation.³⁷ Creating more cost-effective and efficient carbon capture, usage, and storage technologies is critical if researchers are to develop CO₂-derived building materials or other applications.³⁸

See Appendix A for engineering research design priorities at 5, 10, and 20+ year time scales.



• Credit: Convu.

Reactor design engineering is needed to handle new feedstocks and low-temperature transformations using hybrid biological/chemical catalytic transformations for chemical production.

Scaling up sustainable material manufacturing involves increasing production to meet demand while maintaining these sustainable practices. To accomplish this, R&D investment is needed to improve the efficiency and effectiveness of sustainable production methods. This includes engineering more efficient processes to recycle and reuse materials, developing more reliable and sustainable supply chains, and optimizing collection, sortation, and production processes to minimize waste and energy use. Scaling up the collection/transportation/sorting of biodegradable plastics for waste management will also require research to accelerate the transition from cradle-to-grave to cradle-to-cradle.³⁹

Sustainable material manufacturing also requires collaboration and partnerships across industries and sectors. Enabling data sharing about performance through standards and platform development will accelerate broad uptake of more sustainable practices and processes. This involves working with suppliers and customers to promote sustainable practices through engineering and producing sustainable materials that work as well as or better than legacy materials. These new materials must be cost-effective to enable their production and consumption by such users as builders and chemical manufacturers. They must also deliver an improved end-user experience, one that includes both high-quality materials and positive environmental impact.⁴⁰ By adopting improved practices and investing in research and development, companies can produce materials and products that meet growing demand while minimizing the negative environmental impact and promoting circularity.

See Appendix A for engineering research manufacturing and scale-up priorities at 5, 10, and 20+ year time scales.



Apple's Daisy, which can disassemble up to 1.2 million phones each year to help recover valuable materials for recycling.

In 1990, Americans generated approximately 208 million tons of municipal solid waste (MSW). By 2018, that amount had risen to 292.4 million tons, or an average of 4.9 pounds per person per day. Only 32% of that was recycled or composted, and more than half (146 million tons) went into landfills.⁴¹ At current rates, the United States has about 55 years of capacity left in its landfills.⁴² Globally, plastic waste may triple by 2060, with nearly two-thirds of that from packaging and textiles.⁴³ And while a recent study estimated that plastic pollution was entering the oceans at a lower volume than previously thought, it is still growing at nearly 4% annually.⁴⁴

Research to improve materials handling and disposal at the end of useful life—in a way that minimizes waste and maximizes its value—can help mitigate the negative effects of solid waste. Sustainable materials' end-of-use processes are an essential component of the circular economy. This process begins with lifecycle analysis in the design phase that considers all aspects, from using sustainable feedstocks, energy use during manufacturing, transportation resource use, and end-of-life scenarios. Sustainable end-of-life engineering can use easily recyclable materials or design products that can be readily disassembled and repurposed.

The inefficiencies of the plastic recycling industry, as well as the drain on current sources of petroleum required to manufacture plastics, make **engineering compostable polymers** (both synthetic and natural) more urgent. Research into biodegradable plastics (in defined conditions) has been underway since the 1990s. Limits to functionality, scalability, and economic feasibility of production have restricted the use of these polymers. Particular challenges exist in **developing biodegradable flexible food packaging** that can attain FDA approval because of direct contact with food, even as the increasing demand for prepared meals and on-the-go foods has seen food packaging grow into the largest user of petroleum-based plastics in the plastic packaging industry.^{45,46}

However, trade-offs between sustainability factors must be examined. Environmental concerns, technical demands of production and recyclability, economic cost, and social factors, such as consumer participation rates, must be considered to determine which products under development provide genuinely sustainable alternatives to petrochemical plastics.⁴⁸ Recently, plastics produced from the microorganism spirulina have shown promise, both in terms of physical properties and reusability or biodegradability.⁴⁷ Research into modified starch-based food packaging, another potential alternative, must examine how factors such as starch type, temperature and time during film formation, and storage conditions impact the performance of these materials, including their use as moisture barriers. Understanding the potential migration and toxicity effects of nanomaterials in bio-based packaging for food products must also be explored.⁴⁹ Once these factors are better understood, appropriate manufacturing and infrastructure to promote composting can be developed.⁵⁰

As the natural degradation of materials such as plastics or concrete takes several hundred to several thousand years, research to safely accelerate the process is another critical challenge. Various **chemical recycling methods for concrete waste**, such as CO₂ sequestration, appear promising but require more exploration, including environmental and feasibility assessments, to determine the extent of use and scalability.⁵¹ Similarly, engineering research is needed to explore the mechanics of **immobilized enzymes/microorganisms and carbon-based particle/polymer enzyme complexes to degrade microplastics**, as well as the environment in which such operations occur and the safety of degraded material.⁵² Novel chemical recycling should also be explored to augment existing mechanical and solvent-based methods.⁵³

Enhanced chemical recycling, along with **improved plastics sorting technologies at materials recycling facilities (MRFs)**, will improve overall plastics end-of-life scenarios. Currently, MRFs report issues with sorting black plastics (which are difficult to sort because the carbon black pigment absorbs most reflected light from current sorting technologies), film, tangles (plastic ropes, wires, etc., that can slow sorting equipment), adhesives, and mixed-material plastics. While researchers recommend more investigation of AI-driven and robotic sorting, the financial and economic incentives for developing such techniques are lacking.⁵⁴ Recent legislation may offer future motivation; California's new truth-in-labeling law mandates that plastics will only qualify as recyclable if 60% of state residents have access to a recycler that accepts that material and 60% of the state's recyclers have access to a reprocessing facility that accepts it.⁵⁵

See Appendix A for engineering research sustainable material end-of-use and re-use priorities at 5, 10, and 20+ year time scales.

Overall Assessment and Moving Forward

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, plastics, and packaging. Sustainability must become a central feature of products rather than a merely desirable option, and sustainable goods should become the convenient and affordable norm for all consumers. The U.S. engineering research community must play a major role in this transition.

Underlying many of the challenges articulated by participants are three key research themes. Breakthroughs in each challenge area will speed our progress toward a more sustainable society.

Predictive Models/Simulations

As in many areas, the use of AI in materials science is not new, but improvements are needed to transform AI's potential into meaningful impact for future work. The key to future development is creating high-quality and available data related to materials and finding better ways to accurately represent the materials' properties. Better understanding and training of deep learning models must occur to learn how such data is being used.⁵⁶ Priorities for this 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 the biodegradability of new polymers without long-term experimental testing in wet labs.



Credit: Canva



Facilities

Developing new materials will have limited impact unless they 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 gain improved material characterization data in MRFs would assist in creating purer, higher-value waste streams, which incentivizes MRFs to adopt the technology. Importantly, for scale-up efficiency, bioreactor facilities need to be available, scalable, and distributed strategically to ensure minimal carbon footprint.

Biological Processes/Materials

Research into biological processes that inform 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.⁵⁷ Fundamental research must occur to better understand how crop-based feedstocks can be grown at a sufficient scale without competing for crops designated for food production. Much is still unknown about fabricating or regenerating materials using, for example, as grass feedstocks through biogenetic or industrial processes. These materials must be produced efficiently at scale to create carbon-neutral products when compared to current materials. For example, it is critical that researchers develop use-test performance-based mixture proportioning approaches that can maintain the

durability of key building materials, including concrete, while reducing the 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.⁵⁸

Chemical Processes/Materials

While not new processes, CO₂ conversion to useful building blocks, **carbon mineralization, and electrical chemical reduction are still not commercially viable and need engineering resources to optimize and scale efficiently and effectively**. Converting carbon dioxide (CO₂) into carbon monoxide (CO) creates a value-added building block for the chemical industry, since CO is used to synthesize higher-order hydrocarbons for many chemicals and fuels. However, the challenge with converting CO₂ to CO is that CO₂ is non-reactive and requires energy to break its strong bonds.

Carbon mineralization involves reacting CO₂ with minerals to form stable carbonates.⁵⁹ This process sequesters CO₂ and also produces valuable minerals. Research is needed to optimize the catalyst performance to enhance reaction kinetics; the current process is expensive, slow, and energy-intensive. One method requires high temperature and pressure, while the alternative method, suspending in aqueous solutions, suffers from poor dissolution rates. **Engineering research is needed to make carbon mineralization economically viable at scale.**

Electrochemical reduction of CO₂ typically occurs in electrochemical cells or reactors, where a voltage is applied to drive the reduction reactions. This can result in the formation of various products, such as carbon monoxide, formic acid, methane, and ethylene, among others. **Research is needed to enable the use of renewable electricity to drive these reactions, providing a means to efficiently and cost-effectively convert CO₂ emissions into useful and potentially marketable products.**

These reactions are challenging because they produce a mix of products, and controlling the selectivity is crucial for economic viability. Furthermore, catalyst stability and longevity are issues since CO₂ conversion processes can expose catalysts to harsh conditions, including high temperatures and pressures. Engineering should focus on (1) optimizing enzymes that are highly selective; and (2) using genetic engineering or protein engineering to modify the properties of catalysts used for biological reactions in industrial settings to increase their efficiency. This includes altering their stability, substrate specificity, and reaction rates to suit industrial conditions. **Research is needed on different catalysts, electrode materials, and reaction conditions to optimize the selectivity, efficiency, and overall performance of these electrochemical processes from capture to conversion.** This includes minimizing energy requirements, selecting cost-effective catalysts, and considering the overall lifecycle costs. This area of research is of particular interest due to its potential for both carbon capture and utilization, contributing to the development of a more sustainable and circular carbon economy.⁶⁰

There is an urgent need to bring breakthrough materials research and development to the forefront of the nation's zero-carbon target and global sustainability efforts. Companies and their investors are increasingly voicing interest in developing sustainable materials solutions to enable a circular economy. The priorities in this report arise from diverse engineering voices representing academia, large and small industry, and government agencies united by a vision for engineering to transform materials for a more sustainable future. Beginning with three key industries that today contribute significantly to catastrophic greenhouse gas emissions and an unsustainable waste stream is a crucial first step for engineering research to lead in creating a more sustainable future.

Appendix A: Research Priorities by Time Frame

Design

1. 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.

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Develop a theoretical basis for coupled equations, such as electron transport properties that are affected by both electrical conductivity and thermal behavior.</p> <p>Develop lifecycle and metrics collection and create plug-and-play models for different materials and processes.</p> <p>Develop digital representation of polymer systems for large language models (LLMs) to consume since the simplified molecular-input line-entry system (SMILES)⁶¹ is inadequate.</p> <p>Develop universal engineering standards for data labeling, storage, and retrieval.</p> <p>Engineer rapid prototyping/screening methods for new polymers (e.g., polymerization, monomer sourcing, and biodegradability assays).</p>	<p>Develop machine learning (ML) methods for physical prototypes and climate chamber testing to establish minimum thresholds for performance that a higher variety of materials can meet (this requires mechanistic understanding of failure modes or degradation of products/food being packaged).</p> <p>Create a modular materials design platform that uses input specifications to generate a holistic set of design parameters, including technical specifications, cradle-to-grave life-cycle analysis (LCA), etc., and suggest an entire set of solutions.</p> <p>Develop methods to curate, source, validate and manage insufficient data sets to enable ML optimization.</p> <p>Develop lifecycle and metrics collection and standards to create plug-and-play models for different materials and processes.</p> <p>Develop uncertainty quantification of model parameters to identify and refine real-time uncertainties from experimental data in the manufacturing/scale-up phase for feedback to improve design.</p>	<p>Develop multiscale, multi-property predictive models and simulations coupling atomistic to continuum structure property-function relationships that enable the design of materials for biodegradability, mechanical properties, electronic properties, dynamic transport, and chemical properties.</p> <p>Leverage biomimicry in AI-informed materials design.</p> <p>Develop AI-enabled intelligent transformations of materials for use and reuse.</p> <p>Leverage AI and ML for computational discovery of molecules, new synthesis routes, and new ways to combine materials for desired performance.</p> <p>Create a comprehensive, open-source data collection system and database for material properties, structure, and performance with LCA for current materials and new functionality needs.</p> <p>Prioritize human + AI-centered materials optimization to facilitate societal acceptance.</p>

2. Design new reactors and reactor configurations to handle new feedstocks and low-temperature transformations.

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Design new reactors and reactor configurations to (1) handle new feedstocks and low-temperature transformations using hybrid biological/chemical catalytic transformations for chemical production, and (2) reprocess end-of-life materials.</p> <p>Design technology to convert waste to usable products and feedstocks, taking into consideration LCA.</p>	<p>Identify the most efficient reaction pathways for hybrid construction.</p>	<p>Demonstrate flow chemistries on solid/non-petrochemical feedstocks.</p> <p>Develop flow chemistry for solid feedstocks (plastics, biomass, etc.).</p> <p>Develop closed-loop processes for active catalysts.</p>

3. Design efficient hybrid biological/chemical catalytic transformations for chemical production.

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Develop a fundamental understanding of enzymes and catalysts, to include structure-property relationships.</p> <p>Develop efficient and selective catalysts to maximize the conversion of CO₂ into desired products. This involves electrochemical, chemical, or biological processes to optimize reaction conditions, temperature, pressure, and flow rates.</p>	<p>Develop infrastructure for the distribution of CO₂-derived products. This may involve adapting existing distribution systems or creating new ones.</p> <p>Integrate CO₂ conversion processes into existing industrial facilities or design new processes that can utilize captured CO₂.</p>	<p>Investigate novel materials, including advanced nanomaterials and catalytic surfaces, to enhance reaction rates and catalytic efficiency.</p> <p>Leverage advanced computational tools to simulate and predict the behavior of catalysts at the molecular level, aiding in the design of more effective catalysts.</p>

4. Develop a fundamental understanding of how to use biological processes and/or waste, including CO₂, to fabricate and assemble regenerative matter autonomously into desirable structures and then disassemble these structures by design.

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Develop regenerative building blocks or foundational “green” chemicals for materials.</p> <p>Engineer “drop-in” chemistries to replace high-concern substances; eliminate “red list” items.</p> <p>Develop alternative feedstocks to chemical deconstruction.</p> <p>Identify and produce novel building blocks for intelligent-designed materials.</p> <p>Accelerate the innovation cycle of bio-derived materials and their incorporation into materials (including polymers and construction materials) without sacrificing performance.</p>	<p>Develop materials that incorporate one or more waste streams or emissions output as feedstock (e.g., CO₂, CH₄).</p> <p>Design new bio-based polymers from a variety of feedstocks to maintain biodiversity.</p> <p>Design biopolymers from living organisms and produce them at scale with bioreactors.</p> <p>Design new processing methods (specifically for new biomaterials that are inherently more delicate than polyolefins).</p>	<p>Develop materials or materials systems that can grow or be repaired in situ.</p> <p>Decarbonize 100% of chemical production with alternative feedstocks.</p> <p>Improve understanding of CO₂ use applications to materials such as graphene and their emission reduction potential by conducting LCA based on clear methodological guidelines and transparent datasets.</p>

5. Develop sustainable engineered material systems for improved operational construction performance

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Develop traceless degradable or reversible adhesives and binders.</p> <p>Develop binders and compatibilizers to enable the use of mixed waste (including plastic) in construction.</p> <p>Engineer high-performance agricultural wastes or bio-derived materials as feedstocks for construction materials.</p> <p>Develop cross-laminated timber (CLT) from abundant and under-utilized hardwood species available in the United States.</p>	<p>Engineer living materials for multi-functional use, e.g., water and air purification.</p> <p>Develop adaptable architecture resilient to climate change.</p> <p>Engineer self-healing concrete structures using self-healing concrete.</p> <p>Engineer self-cleaning air purification and carbon capture materials and processes for buildings.</p> <p>Create smart building designs for better thermal regulation.</p> <p>Design climate-responsive, adaptive materials systems for buildings.</p> <p>Engineer sustainable materials for industrial decarbonization technologies (e.g., carbon capture adsorbents, battery electrodes).</p>	<p>Engineer road materials that will prevent tire abrasion, avoiding microplastics generation.</p> <p>Determine structural performance tradeoffs from using CO₂ and alternative feedstocks.</p> <p>Develop self-healing concrete that is infinitely usable.</p>

Scale-up and Manufacturing

1. Convert captured CO₂ to useful, high-value chemicals or materials, while assuring that the energy used to drive conversion does not create more CO₂ than is converted.

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Improve the efficiency of converting captured CO₂ into high-value material feedstocks.</p> <p>Develop efficient CO₂ capture technologies from industrial emissions that are scalable for large volumes of CO₂ emissions in the chemical industry.</p>	<p>Engineer efficient scale-up processes for using waste stream/emissions in materials manufacturing.</p> <p>Develop gas fermentation technology to work with mixed gas streams (CO₂, CO, CH₄) and optimize by co-locating with petrochemical operations.</p>	<p>Conduct chemical separations research (e.g., water from biosystems, sugar extraction, CO₂ extraction) to create more energy-efficient separations technologies.</p> <p>Create processes to embed and lock CO₂ into steel and cement during materials production processes.</p>

2. Develop engineering technologies to reduce the cost of industrial biotech unit operations.

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Develop performance-based mixture proportioning approaches that can incorporate materials, chemistry, carbon footprint, cost, and durability.</p> <p>Develop efficient methods to harvest agricultural and post-consumer waste and convert it to energy or matter at scale; for example, an external layer in a building could uptake microplastics and use them to provide energy to the building system.</p>	<p>Accelerate the scale-up of bio-derived materials and their incorporation into polymeric materials without sacrificing performance.</p> <p>Develop manufacturing processes to apply “invisible” packaging to products.</p> <p>Conduct research to scale up equipment for robotic disassembly or dissolution of degradable or reversible adhesives and binders.</p>	<p>Develop new materials that perform at scale to replace fossil fuel-based materials and resources completely.</p>

End-of Use and Reuse

1. Design monomaterial alternatives to multi-layer, single-use packaging for an improved end-of-life scenario that still meets performance expectations.

5–10 YEARS	10–20 YEARS	20+ YEARS
Expand uses of the existing output of end-of-life waste streams.	<p>Engineer novel material designs (e.g., monomaterials and multilayered materials made from a single polymer type).</p> <p>Develop food and product packaging at scale that becomes part of the product when in use or during heating.</p> <p>Engineer water-soluble coatings with high barrier properties for bulk vending machines.</p> <p>Develop packaging that converts waste into food.</p> <p>Design packaging with end-of-life triggers that enable recycling and degradation of multilayer materials.</p>	Develop manufacturing processes to apply traceless “invisible” or edible packaging to products.

2. 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.

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Develop optimized enzymes for polymer breakdown.</p> <p>Develop optimized and nontoxic solvents for polymer dissolution and recycling.</p>	<p>Create novel compost systems (e.g., anaerobic systems, dry fermentation).</p> <p>Conduct extremophile research to understand how to make microbes that consume waste.</p>	<p>Invent new, sustainable enzymes/materials/catalysts.</p> <p>Develop agents to biodegrade cotton and polyester fibers in wastewater systems.</p> <p>Develop reactors that enable new chemical and enzymatic recycling or decomposition technologies to be scaled up.</p>

3. Design new materials for end-of-use recyclability and biodegradability while preserving performance during use.

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Improve connections (adhesives, glues, etc.) to streamline disassembly of construction assemblies into component parts.</p>	<p>Consider the waste streams that will be produced in the materials design stage and optimize catalysts in reactor systems to create the highest waste-stream value for recycling.</p> <p>Develop materials that use sunlight (or another environmental energy source) and trash and convert it to building material, demonstrating that the degradation rate of the material matches the rate of trash input.</p>	<p>Develop infinitely recyclable polymer composition.</p>

4. 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.

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Design sortation processes that consider physical parameters (product shape, flexibility, and weight) as well as chemical and magnetic signatures.</p> <p>Create computational tools to track building construction materials and value after construction.</p> <p>Develop rapid analytical technical processes to separate mixed waste streams effectively, leveraging AI.</p> <p>Develop methods for rapid screening of toxic legacy substances in post-industrial and post-consumer waste.</p>	<p>Develop technology for working with mixed waste.</p> <p>Develop resource distillation to eliminate the need to separate waste.</p> <p>Engineer biological/chemical sorting and separation for the broad, challenging waste streams that cannot be separated via mechanical recycling.</p> <p>Develop technologies to efficiently extract critical materials from complex items (e.g., waste, crushed concrete, solar panels, wind turbines, etc.).</p>	<p>Conduct robotics/ME/EE research to automate the removal of mechanical connections (e.g., screws) to facilitate disassembly of construction assemblies.</p>

5. Develop computational methods to predict the biodegradability of new polymers with minimal experimental data – without long-term experimental testing.

5–10 YEARS	10–20 YEARS	20+ YEARS
<p>Develop databases and AI models to predict polymer properties from biological/chemical monomers.</p>	<p>Develop robust computational models for predicting end-of-life scenarios.</p>	<p>Close the loop with respect to experimental characterization, using design space determined from models and simulations.</p>

Appendix B: Visioning Event Participants

Alaaeddin Alsaiee, BASF

Jeff Bates, University of Utah

Val Chiykowski, Evok Innovations (Evok)

Jennifer Dionne, Stanford University

Erin Gately, Iron Mountain

Juan Pablo Gevaudan, Pennsylvania State University

Aletheia Ida, Designing WELL

Burkan Isgor, Oregon State University

Robert Kennedy, Aeternal Upcycling

Michael Koepke, Lanza Tech

Raj Krishnaswamy, CJ Biomaterials

Kim Kurtis, Georgia Institute of Technology

Laurent Matuana, Michigan State University

Lindsay Mendes, SABIC Ventures

Romain Metivet, Cellulotech Inc.

Sabbie Miller, University of California, Davis

Minal Mistry, Oregon Department of Environmental Quality

Molly Morse, Mango Materials

Kevin Musselman, University of Waterloo

Ramani Narayan, Michigan State University

Sridevi Narayan-Sarathy, PepsiCo

Shar Olivier, KIELY Family of Companies

Punnag Padhy, Stanford University

Jed Pitera, IBM Research

Nicholas Rorrer, National Renewable Energy Laboratory

Eleftheria Roumeli, University of Washington

Daniel Sanders, IBM Research

Blake Simmons, Lawrence Berkeley National Laboratory

Anish Tilak, Rocky Mountain Institute (RMI)

Orlin Velev, North Carolina State University

Bob Versluys, Sonoco Products Company

Yael Vodovotz, The Ohio State University

Fei Wang, Procter & Gamble

Greg Wellman, Eastman Chemical Company

Alison Wilders, Danimer Scientific

Brandon Wray, National Ready Mixed Concrete Association (NRMCA)

Jingjie Yeo, Cornell University

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Sandy Mau, UIDP

Pramod Khargonekar, University of California, Irvine

Annie Shealy, ERVA

Rebecca Silveston, ERVA

Appendix C: Visioning Event Presentations

Opening Panel

Moderators: Jennifer Dionne, Stanford University; Yael Vodovotz, The Ohio State University

Panelists: Nicholas Rorrer, National Renewable Energy Laboratory; Anish Tilak, Rocky Mountain Institute; Ramani Narayan, Michigan State University

This panel began by posing a simple fact—regardless of our future, we will still need materials, whether these are familiar or completely different from what we know today. Materials are needed for the essentials of existence: food, clothing, and shelter. Although AI and digital tools will help shape the new materials reality, materials scientists and engineers will still be critical. Life cycle analysis (LCA) will also play a greater role as engineers seek better end-of-life materials scenarios. Rather than being a liability in the quest for carbon-neutral environments, materials must be part of the solution. Building materials, for example, should actively or passively sequester carbon. They should be engineered to be more self-healing and infinitely usable, enabling more circularity.

The panelists then considered a future project each would undertake, given the resources to do so. One idea focused on the shift from internal combustion engines to electric vehicles—how that would influence chemical manufacturing, how that would presuppose different building blocks for vehicles— and how it might change how tires produce degradable microplastics on roads, for example. Another involved creating a systems planning project that considered synergies between types of buildings and materials required to construct them—to design with more intention than is done today. Innovation in AI could help track data and the value of materials used in construction so that extraction and reuse become more possible. A third idea was looking at LCA holistically, from acquiring feedstocks to managing materials' end-of-life and to more efficiently separate materials and transform them into useful and reusable components. Closely allied to this is considering how to approach agricultural processes in a way that enables 100% use of waste products.

In response to audience questions, the panelists noted that the biggest chemical issues and challenges today relate to supply chains, scalability, and cost. Determining systems and meaningful, scalable processes for composting and reclaiming materials will involve advances in individual, neighborhood, and industrial composting units. Regional differences must also be taken into account. In terms of increasing the use of biobased polymers on a global scale, scarcity tensions between food and feedstock production must be negotiated.

A Case for Sustainability

Presented by Sabbie Miller, University of California Davis and Lawrence Berkeley National Laboratory

Nearly a third of greenhouse gas emissions in 2016 came from the production, use, and disposal of materials. Nearly 30 gigatons of cement-based materials were consumed in 2016, making it the most used construction material. However, water was the most consumed resource at 4,000 gigatons. Key drivers of this consumption are population, technology, and affluence. Technologies can both enable greater consumption and mitigate the use of resources. Because certain materials are so commonly used for specific functions, they become locked in as we continue to use and maintain structures. This keeps the use of the non-sustainable materials cycle moving and contributes to continued consumption. Performance is also a factor, as users hesitate to adopt new materials that do not perform at accustomed levels.

Miller used concrete consumption as an example of how engineers and society see materials use as adjacent to nature. Resources are extracted in ways detrimental to the natural world. She discussed ways engineering can create more efficient use of concrete (Figure 1, below) and then considered some engineering limitations throughout the material lifecycle.

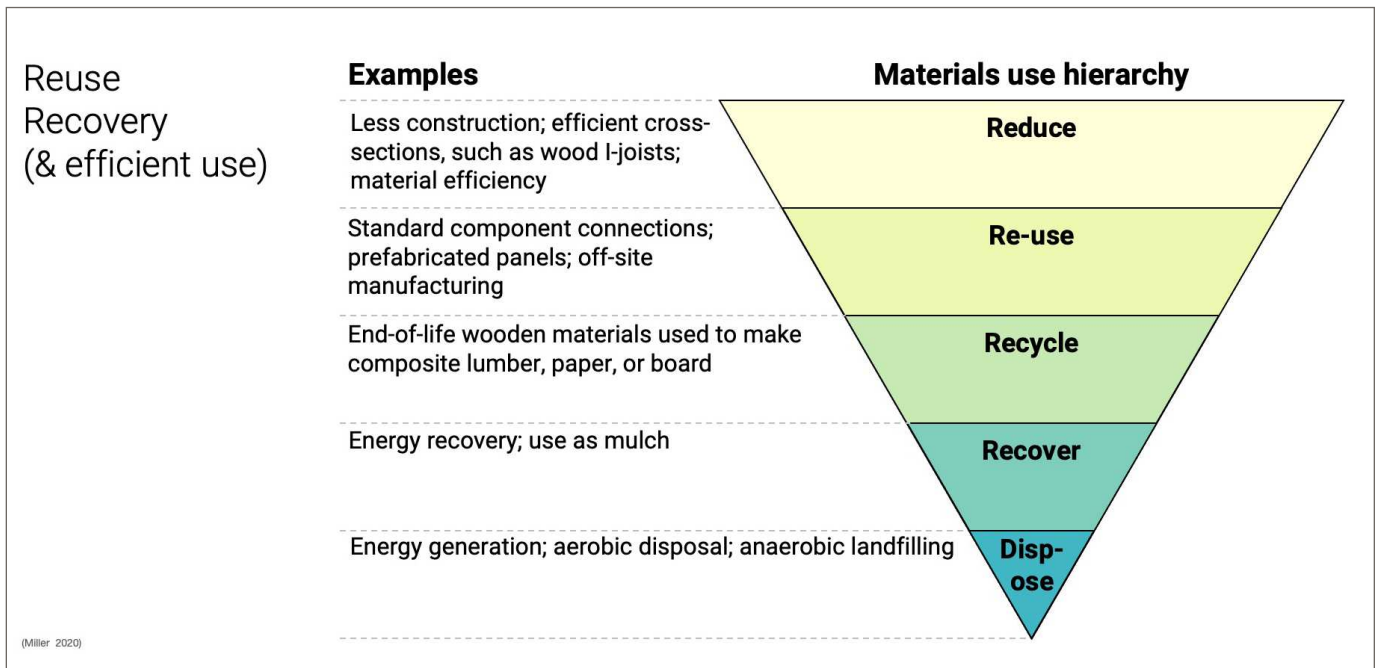


Figure 1: Engineer for Reuse and Recovery

KEY LIMITATIONS INCLUDE:

- Increasing the impact of one or more factors while mitigating another;
- Balancing the local, regional, and global impacts of decisions;
- Compromising one lifecycle stage for another;
- Using inappropriate metrics for analysis;
- Assuming particular behaviors in the future; and
- Slow rate of advancement and incremental change.

The differential rate of advancement and incremental change is critical as engineers balance elements of systems to meet changing needs.

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