LEARN AND GROW TOGETHER

UTAgRESEARCH
INSTITUTE OF AGRICULTURE
THE UNIVERSITY OF TENNESSEE

EMBRACING COMPLEXITY

CIRCULAR BIOECONOMY SYSTEMS ROADMAP

EXECUTIVE SUMMARY

This Circular Bioeconomy Systems (CBS) report describes a mobilizing framework inspired by the insights and outcomes gained from the inaugural Bioderived Materials and Chemicals in CBS Conference held on September 3–4, 2025, in Pigeon Forge, Tennessee. This landmark gathering united thought leaders from academic, industry, government, and non-profit organizations to address the pressing challenges and seize the opportunities of transitioning to a circular bioeconomy. This roadmap serves as a strategic guide to researchers, businesses, funding agencies, policymakers, and other stakeholders to foster systemic transformation in resource utilization. It advocates for moving beyond outdated linear models toward regenerative circular models that prioritize system resilience and prosperity for all citizens through economic growth that aligns with environmental stewardship and societal well-being.

Advancing CBS requires a coordinated approach that addresses current challenges while driving sustainable innovation, adoption, and impact. The following priorities synthesize actionable pathways identified through stakeholder engagement and expert analysis during the conference. Optimizing biomass utilization and supply chains is essential, given the diverse and complex nature of biomass, which makes sorting, separation, purification, and logistics both costly and energy intensive. To overcome these hurdles, we must leverage advanced tools like artificial intelligence (AI) and machine learning (ML) to develop effective technologies for processing underutilized biomass streams into high-value products and achieve circularity. Product design should anticipate unavoidable losses, embed end-of-life solutions to maximize carbon retention, prioritize nutrient return to soils, and support localized supply chains for resilience. Establishing standardized metrics and robust data infrastructure is critical for effective benchmarking and cross-sector comparability. Clear product labeling along with integrated systems that capture technical, economic, environmental, and social dimensions will improve transparency, track material flows, and inform decision-making. Policy frameworks must be unified and built through multi-stakeholder collaboration to align incentives, balance trade-offs, and maximize synergies at both local and national levels. Bridging the gap between academic innovation and industry implementation requires multidisciplinary partnerships and coordinated investments in demonstration facilities to accelerate technology transfer. Awareness of consumer preferences along with the promotion of use-inspired innovations that match conventional products in performance and familiarity will drive market adoption and incentivize industry investment. Advancing workforce development and community engagement will address limited awareness of CBS careers, insufficient training opportunities, and a lack of standardized certifications, especially in rural regions where advanced manufacturing facilities will be located. Expanding K–18 education initiatives, vocational training programs, certifications, and industry-led modules will cultivate a skilled workforce. Early community outreach and hands-on learning will ensure broad participation and acceptance of sustainable practices and circular products.

The CBS Conference created momentum among participants by accepting the inherent complexity and embracing multidisciplinary systems thinking to transition to a circular bioeconomy. By integrating the strategic priorities identified above into every aspect of CBS advancement, we will overcome barriers and catalyze robust circular bioeconomy systems that deliver lasting benefits for communities, industries, and future generations.

CONTRIBUTING AUTHORS

University of Tennessee
Center for Renewable Carbon
Nicole Labbé
Jenny Moore

UTAgResearch
Jessica McCord
Timothy G. Rials

University of Tennessee-Oak Ridge Innovation Institute
Mary Danielson
Raphael Ployet
Umesh Marathe
Ahmed Chennak
Somnath Koley

University of Georgia
College of Agricultural & Environmental Sciences
Brahm Verma

Department of Agricultural & Applied Economics
Gopinath Munisamy

Virginia Polytechnic Institute and State University
Department of Food Science & Technology
Haibo Huang

North Carolina State University
Biological and Agricultural Engineering
Joe Sagues

HudsonAlpha Institute for Biotechnology
BRIDGES Engine
Samuel Jackson

agInnovation South
Southern Association of Agricultural Experiment Station Directors
Gary Thompson

Oak Ridge National Laboratory
University of Tennessee-Oak Ridge Innovation Institute
Rebecca Wilkes
Diego Hincapie

SPONSORSHIPS

Financial support was provided by the University of Tennessee (UT) Office of Research, Innovation, and Economic Development; UT AgResearch of the University of Tennessee Institute of Agriculture; the UT Center for Renewable Carbon, and the University of Georgia College of Agricultural and Environmental Sciences.

INTRODUCTION

The global economy continues to operate in a predominantly linear flow in a “take > make > waste” model. Currently, only 6 percent of all materials processed by the economy are recycled while half of material and energy inputs leave the economy within a year (circle economy, 2025; haas et al., 2015; Langholtz et al., 2024). In recent years, the concept of circular bioeconomy systems (CBS) has been increasingly recognized by scholars, practitioners, businesses, non-governmental organizations, and policymakers as an economically viable alternative to replace the dominant use-and-dispose linear economy. CBS emphasizes optimally harnessing the potential of bioresources by closing the loops of material and energy flows, extending the lifecycle of products circulating in the economy, and enhancing the efficient use of biomass and waste. By doing so, CBS offers a pathway to accelerate and facilitate the transition to a more resource-positive society and reframe the concept of “waste” into a valuable resource.

CONFERENCE SCOPE AND PURPOSE

To tackle critical challenges surrounding sustainable resource utilization and engage researchers in addressing scientific and engineering gaps within the CBS framework, we hosted the Bioderived Materials and Chemicals in Circular Bioeconomy Systems Conference. This pivotal event, held September 3-4, 2025, in Pigeon Forge, Tennessee, was co-hosted by the University of Tennessee, Virginia Tech, North Carolina State University, University of Georgia, HudsonAlpha Institute for Biotechnology, and agInnovation South. The conference aimed to highlight unique perspectives and

CONFERENCE OBJECTIVES

The primary objectives of the conference were to:

1. Highlight cutting-edge research focused on circularity principles in bioderived materials and chemicals.
2. Strengthen partnerships with regional industries committed to advancing circularity while aligning academic research priorities with industry needs through group discussions and networking.
3. Identify critical information gaps and data needs to accelerate CBS deployment.
4. Explore innovative approaches and strategies for securing funding to support CBS initiatives.

transformative opportunities that CBS concepts offer for fostering sustainable development and advancing the rural economy of the Southeastern region. By leveraging the region's abundant, biogenic carbon resources, participants explored innovative pathways to enhance resource efficiency and sustainability. The conference expanded on themes emerging from recent workshops conducted by the American Society of Agricultural and Biological Engineers (ASABE, 2024). In addition to thought-provoking presentations and discussions, the conference provided extensive networking opportunities for academic, government, and industry stakeholders. Attendees noted that the event reinvigorated enthusiasm for advancing CBS initiatives, inspiring them to bring renewed energy and ideas back to their respective organizations.

The conference brought together experts from various disciplines to exchange insights from research and development organizations focused on circularity principles to drive future innovation. A key theme emphasized optimizing the recovery and reuse of renewable carbon to extend its lifetime and maximize its value in the marketplace. The organizing committee featured CBS thought leaders from prominent institutions across the Southeast, including Tim Rials and Nicole Labbé (University of Tennessee), Brahm Verma and Gopinath Munisamy (University of Georgia), Haibo Huang (Virginia Tech), Joe Sagues (North Carolina State University), Sam Jackson (HudsonAlpha), and Gary Thompson (agInnovation South). The eighty-four attendees from twelve U.S. states and four countries (USA, Canada, Chile, and The Netherlands), included senior and junior faculty, postdoctoral fellows, and students from twenty-five institutions, professionals from seven industries, leaders from seven non-profits institutions, and researchers from three national laboratories.

These objectives were addressed through a variety of engaging formats, including keynote presentations, concurrent research sessions, industry panel discussions, workshop discussions, and poster exhibitions. Institutions across the U.S. and the world are actively conducting research and development on individual components of circular materials and chemicals.

Day one featured two inaugural keynote speakers who set the stage with foundational perspectives on CBS. Guus ter Haar from Circle Economy presented on "Tackling the global circularity gap" while Orlando Rojas from the University of British Columbia discussed "Innovations in Bio-Based Chemicals and Materials: A Colloidal Systems Approach." Their insights sparked thoughtful discussions among participants. Following the keynote addresses, technical sessions included presentations by invited leading scientists and members of the broader research community (for specific presentation topics, refer to CBSconference.tennessee.edu). These sessions focused on two key topics: Engineering Sources of Sustainable Carbon and Design of Circular Product Systems. In the afternoon, an industry discussion panel brought together experts from various organizations, including Corey Tyree (Trillium Renewable Chemicals), Jorge Gonzalez (UL Research Institutes' Materials Discovery Research Institute), Scott Kuhlman (ReCircled), Brewer Logan (Verenovo), Larissa Fenn (Rayonier Advanced Materials, Inc.), and Gerry Heebner (Kraton Chemical, LLC). This was followed by breakout working groups aimed at identifying current gaps in CBS research. The day concluded with a poster session showcasing work by graduate students and junior researchers. This session provided valuable networking opportunities for academic and industry professionals to connect and exchange ideas.

Day two of the conference featured a series of technical sessions, each consisting of twenty-minute presentations that delved into four key topics: Modeling Applications in CBS, Sustainable Manufacturing: Industry Challenges and Collaborative Solutions, Networking for Innovation: Collaboration Opportunities in CBS, and Building the Future: Education and Workforce Development. The afternoon began with a panel discussion on research strategies and partnerships, and regional industry commitments for accelerating deployment of CBS Programs. This panel included Kirsten Allen (Schmidt Sciences), Brad Day (University of Tennessee), Stephanie Herbstritt (Clean Air Task Force), Gary Thompson (agInnovation South), and Sarah Sullivan (Kraton Chemical, LLC). The day concluded with report-outs and closing remarks, summarizing key takeaways.

DEFINING CIRCULAR BIOECONOMY

The group discussion session focused on defining circular bioeconomy, emphasizing its adaptability across different scenarios, industries, and user groups. Circular bioeconomy was described in various ways: as a system that uses biomass as an input instead of non-renewable material streams; as the closing of resource loops spanning feedstocks, supply chains, and markets; as context- and region-specific rather than universally defined; and even as a mindset or design strategy aimed at eliminating waste by designing products to prevent waste from the outset. This intentionally flexible approach to defining CBS encourages broad participation beyond biomass-focused stakeholders and facilitates the development of a comprehensive framework for CBS (Fig 2).

HIGH-LEVEL CHALLENGES

The engaging and insightful discussions throughout the conference generated a wealth of collective knowledge, highlighting several challenges that need to be addressed to advance CBS.

Heterogeneity of Biomass and Widespread Distribution

The diverse and complex nature of different streams of biomass presents significant challenges. Processing such as sorting, separation, deconstruction, fractionation, and purification are costly and require substantial energy input. Additionally, identifying and collecting low-density biomass, which is widely distributed across vast landscapes, poses logistical and financial challenges. Complete utilization of biomass is often impractical or inefficient. Therefore, product design should account for inevitable losses, embed end-of-life solutions to maximize carbon retention, and prioritize the return of nutrients to soils.

Standardized Metrics

Developing standardized methods to assess factors such as biodegradability, emissions, energy consumption, transportation costs, and product lifetimes is essential for the viability of CBS. However, a “benchmarking dilemma” arises when comparing innovative bioproducts to existing materials that often serve different functions. This makes it difficult to demonstrate the value of novel solutions that are not direct “drop-in” replacements for conventional materials.

Academic-Industrial Collaboration

Academic research frequently emphasizes exploring possibilities and innovations while industry tends to prioritize evaluating the practicality and rationale behind those advancements. Effective implementation strategies, economic feasibility assessments, and robust risk management are essential for successfully establishing new technologies.

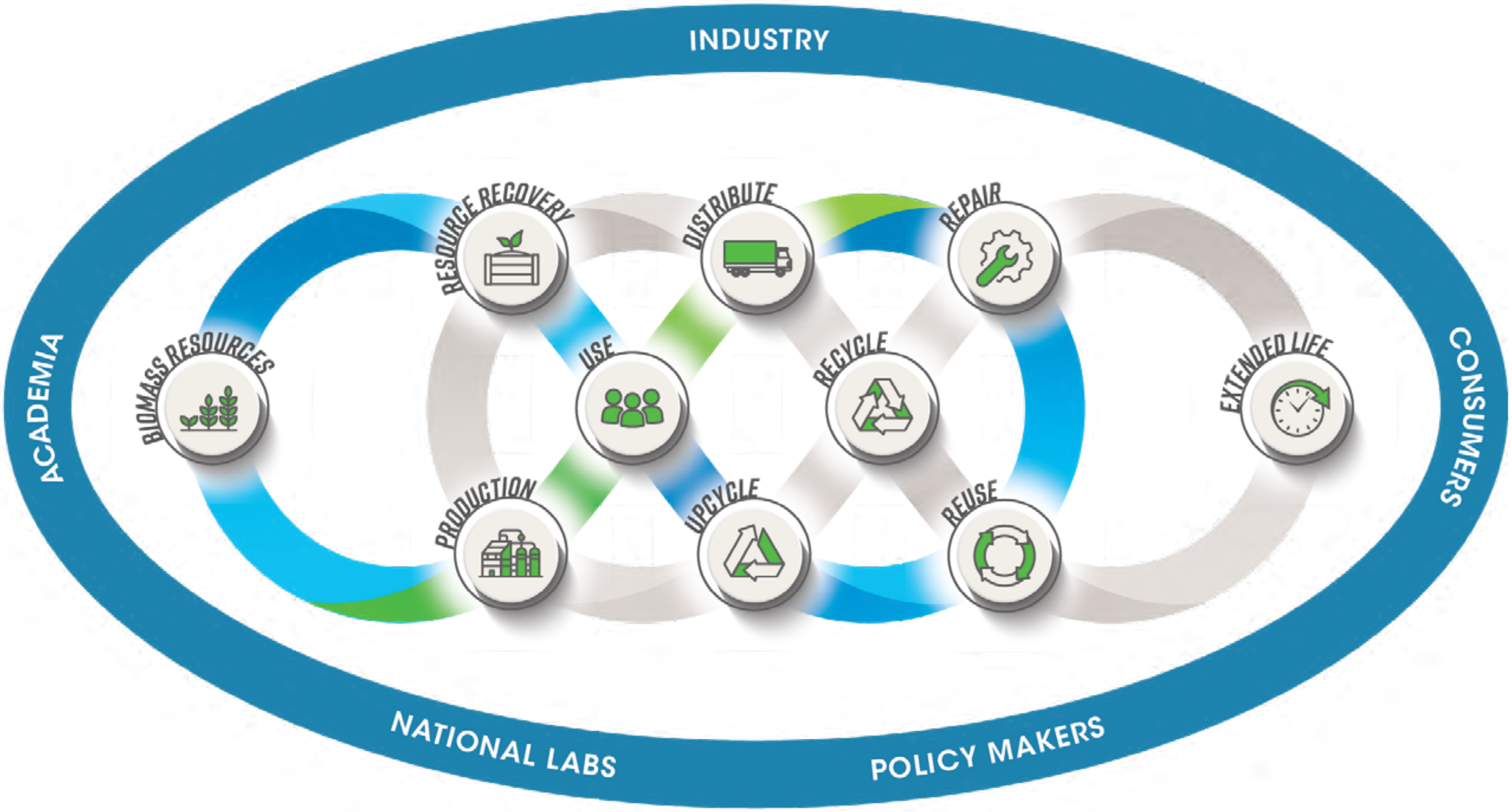


Fig 2. *Comprehensive framework of the CBS flexible approach.*

Data Transparency and System-Wide Information

A significant inefficiency lies in the lack of reliable, transparent, accessible, and non-proprietary data regarding the availability, characteristics, and costs of distributed waste streams. Additionally, establishing a robust system-wide data infrastructure, including clear and consistent product labeling, is essential. Such measures will enable effective tracking of materials to ensure their proper reintegration into biological or technological cycles.

Social Acceptance

Understanding consumer and producer behavior is essential for effectively communicating product solutions and their benefits. However, research often concentrates on technical aspects, neglecting critical factors such as motivating individuals, fostering trust, community needs, and bridging the gaps between academia, industry, and communities. Developing social science-based analytical frameworks that enable us to understand and project consumer and producer decisions and values is essential to drive research on the development and deployment of technical solutions.

Workforce Development

Engaging students early and consistently through both formal and informal educational initiatives is essential. A local skilled labor force capable of processing biomass and operating advanced manufacturing facilities is particularly important, as these facilities are often situated in rural communities. Providing educational opportunities to residents in these areas is crucial for fostering the necessary expertise and supporting the growth of sustainable industries.

PRIORITY 1:

DEVELOPING TECHNOLOGIES FOR THE CBS TRANSITION

The transition to sustainable CBS hinges on the development of advanced technologies that enable efficient separation, processing, and conversion of diverse and underutilized biomass streams into high-value outputs. These outputs support both consumer (“business-to-consumer” B2C) and industrial markets (“business-to-business” B2B), linking agriculture, manufacturing, and end-use sectors into closed-loop supply chains. Strategic investments in technology are essential to overcome current limitations in biomass utilization and unlock scalable and circular pathways for materials, chemicals, and energy.

Recent advances span from crop engineering to industrial manufacturing. Modern plant biotechnology enables the design of feedstocks not only for yield but also for specific industrial traits, such as oilseed crops engineered for unique fatty acid profiles or metabolic redesigns that boost oil accumulation without expanding cropland. Such targeted improvements enhance both the quality and quantity of feedstocks available for CBS applications.

Feedstock diversification further strengthens supply chain resilience. Dedicated fiber and energy crops like switchgrass, miscanthus, hybrid poplar, soybean, camelina, and pennycress provide a range of raw materials—fibers, lignin, cellulose, and lipids—that can be converted into bioplastics, platform chemicals, composites, and bioenergy intermediates (Dadi et al., 2025). Companies such as Genera in Tennessee exemplify the industrial relevance of these innovations by producing compostable packaging from regionally grown biomass and marketing process byproducts across multiple industries.

Despite these advancements, challenges remain. The complexity and heterogeneity of feedstocks, incomplete biomass utilization, regional disparities in availability, transportation inefficiencies, and limited infrastructure for processing natural fibers hinder broader adoption. Addressing these gaps requires continued innovation in biorefining, particularly scalable methods for efficient deconstruction and purification of lignocellulosic biomass (Baranwal & Merino, 2025; Zhang et al., 2018).

On the laboratory scale, valorization of byproducts like lignin and used plastics has led to bio-based materials that rival conventional polymers in performance. Lignin-derived polyols are now used in insulation foams with competitive thermal properties. Research also continues into biofuels from unconventional feedstocks and advanced recycling techniques such as mechanical, chemical (e.g., alcoholysis/aminolysis), pyrolysis, and hydrothermal liquefaction, that can reconstruct new materials from mixed waste streams. However, low consumer participation rates (about 32 percent recycling/composting), confusion about recycling practices, high costs, and contamination remain significant obstacles to effective system-wide recycling.

PRIORITY 1 Developing technologies for the CBS transition	PRIORITY 2 Enabling industrial scale-up and market integration	PRIORITY 3 Developing standard metrics and policies	PRIORITY 4 Engaging the community and building the workforce
• Advance feedstock utilization • Develop scalable and modular bioprocessing • Innovate product design and engineering, recycling, and upcycling • Integrate data science tools (e.g. AI, ML, -omics)	• Bridge the technology readiness gap • Drive market acceptance and adoption • Align incentives among diverse interest groups to maximize synergies and minimize conflicts	• Establish standardized multidimensional metrics that encompass technical, economic, environmental, and social dimensions of CBS • Establish consensus on policy frameworks that support socially desirable transitions to circularity	• Increase workforce awareness and engagement • Develop training pathways and certifications • Promote experiential and value-based learning • Involve stakeholders in business model design research

Table 1. *Priorities for transitioning to CBS in the Southeastern U.S. with highlighted goals for each priority area.*

Emerging bioconversion technologies that leverage systems biology, synthetic biology, and genetic engineering are expanding the range of products obtainable from biomass and waste streams. Modular biorefineries embedded within existing infrastructure offer opportunities to maximize resource efficiency while supporting local economies.

Innovation in CBS also means rethinking "efficiency." Rather than relying solely on large-scale operations and global supply chains, smaller modular systems can be more adaptable to local needs and less vulnerable to disruption. This distributed approach supports rural economic development while increasing system resilience. Looking ahead, integrating AI, machine learning, robotics, and genetic engineering will be critical for optimizing process control, predictive material design, automation of recycling/sorting processes, and extending product lifetimes through self-healing or self-assembling materials.

Importantly, CBS involves multiple stakeholders, including farmers, biorefineries, manufacturers, and consumers, and must address not only technological but also economic and social dimensions. Social acceptance depends on transparent communication about the benefits of circular products; workforce development requires education initiatives at all levels; and policy frameworks must support collaboration across sectors.

Grand research questions that will help address technical challenges for CBS are:

- What fundamental design principles and technological strategies will allow bio-based materials to achieve both high performance and inherent recyclability, ensuring their seamless integration into circular supply chains supported by innovative fractionation methods and intelligent manufacturing systems?
- How can CBS strategies be designed to maximize both environmental sustainability (e.g. carbon retention and nutrient cycling) and social acceptance among diverse stakeholder groups, including rural communities?
- What approaches most effectively foster consumer trust and behavioral change toward circular products made from waste or non-traditional feedstocks, and how do these perceptions influence market adoption at regional versus national scales?

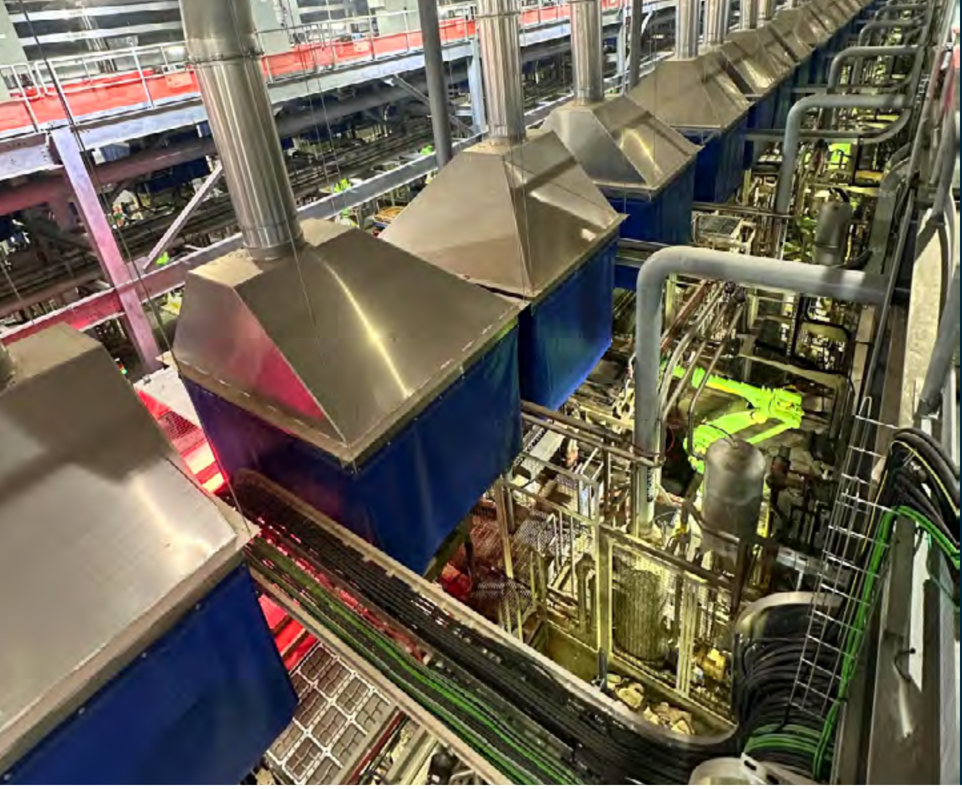
PRIORITY 2:

ENABLING INDUSTRIAL SCALE-UP AND MARKET INTEGRATION

Transitioning to a robust circular bioeconomy is a national imperative that requires more than technological breakthroughs; it demands an integrated strategy for scaling up innovation and ensuring widespread adoption. The journey from the laboratory to real-world impact is often hindered by critical gaps in funding, infrastructure, and market acceptance. Addressing these barriers is essential for unlocking the full potential of CBS to deliver sustainable economic growth, environmental stewardship, and societal benefits.

One of the most significant challenges in this transition is bridging the so-called "valley of death" between technology readiness levels (TRLs) 4–6. While academic research continues to generate promising solutions at the lab scale, many technologies stall before reaching industrial deployment due to insufficient capital investment, limited access to demonstration facilities, and a lack of coordinated public–private partnerships (Watson et al., 2025). Overcoming this bottleneck requires targeted investments in pilot-scale validation and demonstration infrastructure. By de-risking emerging technologies through real-world testing and facilitating their integration into supply chains, we can accelerate commercialization rates, create high-quality jobs, and foster regional economic development.

A central component of this strategy involves embedding regional circularity within broader national



Several grand research questions emerge as priorities for scaling up and adopting innovations in circular bioeconomy supply chains:

- How can targeted investments in pilot-scale validation, demonstration facilities, and public–private partnerships accelerate the transition of CBS technologies from laboratory prototypes to economically viable industrial-scale applications?
- What strategies can effectively integrate regional circularity within national frameworks, enabling localized valorization of feedstocks while enhancing resilience, economic growth, and security against global disruptions?
- How do consumer perceptions, market preferences, and societal acceptance influence the adoption of circular bioeconomy innovations (especially those utilizing waste as inputs), and what design principles can ensure bio-based products achieve "drop-in" equivalence with conventional materials to foster rapid market uptake?

frameworks. Localized systems that valorize region-specific feedstocks offer clear advantages: they reduce transportation burdens, enhance supply chain resilience, and enable communities to capture greater economic value from their natural resources (Bringezu et al., 2021). These systems also contribute to national priorities such as energy security and rural revitalization by building economic buffers against global disruptions. Achieving this vision will require new models for cross-sector collaboration, engaging stakeholders from agriculture, manufacturing, logistics, and policy to ensure that CBS solutions are both scalable and adaptable to diverse regional contexts.

Equally important is driving the adoption of CBS innovations through alignment with market needs and societal values. Economic profitability, ecological sustainability, and societal acceptance are all critical determinants of success. On the supply side, it is essential that new processes and technologies are not only technically feasible but also economically attractive for industry partners. Early engagement with stakeholders, including manufacturers, investors, and local governments, can help identify pathways for cost reduction, risk mitigation, and value creation. On the demand side, consumer perceptions play a decisive role in determining market acceptance. Products derived from waste streams or non-traditional feedstocks may face skepticism regarding quality or safety. However, when consumers recognize added value, such as environmental benefits or superior performance, they are more likely to support circular products and even pay premium prices. To foster this trust, outreach campaigns must communicate the tangible benefits of CBS innovations while behavioral research will help uncover drivers of consumer choice. Prioritizing use-inspired innovations that deliver "drop-in" equivalence with conventional materials, in terms of appearance, feel, and performance, will further lower barriers to adoption by ensuring seamless integration into existing markets. The transformative impact of this approach lies in its ability to deliver measurable outcomes across multiple dimensions. By advancing more technologies past TRL 6 within defined timeframes, we can demonstrate increased commercialization rates and tangible job creation in key regions. The development of scalable models for regional circularity will provide blueprints for replication nationwide, amplifying impact far beyond initial pilot sites. Furthermore, these efforts will generate high-impact metrics, such as reductions in carbon footprint or improvements in rural economic resilience that directly align with federal agency missions related to decarbonization, innovation ecosystems, and workforce development.

PRIORITY 3:

DEVELOPING STANDARDIZED MULTIDIMENSIONAL METRICS, A CIRCULAR SUPPLY FRAMEWORK, AND GUIDING POLICIES

The successful transition to CBS in the U.S. also requires a unified framework for measuring progress, aligning incentives, and guiding policy. While technical advances will continue to accelerate the shift toward circularity (Fullerton, 2025), the absence of standardized metrics and cohesive policy remains a critical barrier to widespread adoption and impact (Chennak et al. 2024). To address this gap, we propose a strategic focus on developing empirically grounded, multidimensional frameworks that integrate technical, economic, environmental, and social dimensions of circular supply chains. These frameworks will provide the analytical foundation for identifying key transformations across every stage of the supply chain as industries move from linear to circular models. By systematically mapping costs, benefits, and stakeholder interests, these models will reveal where market failures or rebound effects may arise, ensuring that new strategies do not inadvertently generate more waste or inefficiency.

Central to this effort is the creation of standardized circularity metrics and indicators. A unified system will enable consistent assessment and benchmarking of CBS performance at the product, process, and system levels, across sectors and regions. Technical metrics will track energy and biomass flows; environmental metrics will quantify reductions in ecological impact; economic metrics will capture value creation and cost savings; social metrics will evaluate workforce development and community well-being. Leveraging advanced tools such as life cycle assessment (LCA), techno-economic analysis (TEA), data envelopment analysis (DEA), and system dynamics modeling will ensure that these metrics are both rigorous and actionable.

These frameworks and metrics are not only essential for monitoring progress, but they are also powerful tools for guiding innovation investment and informing evidence-based policy. They will allow agencies to identify which bio-based innovations deliver the greatest societal benefit, where adoption bottlenecks persist, and how best to design incentives that maximize participation from all stakeholders. Critically, they will provide transparent benchmarks for industry and consumers alike, building trust in CBS products and practices.

The workshop discussions frequently highlighted the transformative power of integrated policy. For example, a commission in the European Union (EU) reports that adopting circularity as an essential element of business models is key to ensuring long-term competitiveness of businesses (European Commission, 2018). The EU's Circular Economy Package, introduced in 2014 and later revised in Closing the Loop - An EU plan for the Circular Economy, reflects this commitment. Similarly, Japan has prioritized circularity through decades of policies culminating in the Sixth Basic Environmental Plan (Environment, 2024). In contrast, the U.S. policy landscape remains fragmented.

However, only 32 percent of municipal solid waste (MSW) were recycled and composted; and confusion about recycling practices, high costs, and contamination remain significant obstacles to effective system-wide recycling (U.S. Environmental Protection Agency, 2025).

By investigating these foundational research questions, we will address the need for robust measurement tools, collaborative policy frameworks, and safeguards against unintended consequences, each critical for advancing a scalable and socially desirable circular bioeconomy:

- How can integrated, multidimensional frameworks and standardized metrics be developed to accurately assess circularity performance across technical, economic, environmental, and social dimensions at product, process, and system levels to enable evidence-based decision-making and policy design for CBS?
- What strategies and policy mechanisms are most effective in fostering consensus and collaboration among diverse stakeholders, including producers, manufacturers, policymakers, and consumers, to drive the adoption, profitability, and scalability of circular supply chains in the U.S.?
- How can market failures and rebound effects be identified and mitigated within circular supply chain transitions, ensuring that circularity leads to genuine sustainability outcomes rather than unintended increases in waste or inefficiency?

PRIORITY 4:

ENGAGING THE COMMUNITY AND BUILDING THE WORKFORCE FOR A SUSTAINABLE CIRCULAR ECONOMY

A thriving circular bioeconomy depends not only on technological innovation but also on cultivating a diverse, skilled, and engaged workforce that reflects the needs and values of the society ("The service-based bioeconomy," 2014). Yet, careers in science, mathematics and technology, especially those related to CBS, often suffer from low visibility and perceptions of being difficult or inaccessible (El-Chichakli et al., 2016). This situation is compounded by limited real-world learning opportunities, insufficient CBS content in educational curricula, a lack of standardized certifications, and inadequate funding for content development. As a result, many students and workers remain unaware of or unprepared for emerging opportunities in the bioeconomy.

To overcome these barriers, it is essential to systematically assess unmet bioeconomy workforce needs and use these insights to design multilevel workforce training programs that inspire early interest (K–18), upskill current professionals, and foster lifelong learning. Nationally recognized, certified training pathways, developed through public–private partnerships, can ensure quality and consistency while meeting industry demands for advanced technical skills. Leveraging models such as Manufacturing USA regional institutes can accelerate program deployment and scalability.

Financial incentives are critical to stimulate collaboration between academia, industry, and community organizations. These partnerships can support curriculum co-design for vocational training, diploma programs, graduate degrees, mid-career certifications, and flexible online courses. Industry involvement is particularly valuable for delivering short modules on advanced bioprocessing technologies and safety standards, ensuring that academic training remains aligned with evolving workforce needs.

Innovative teaching methods are needed to make CBS education engaging and accessible. Interactive classes, technical workshops, apprenticeships, and hands-on experiences can bridge the gap between theory and practice. Outreach initiatives that connect CBS efforts to tangible community benefits, such as waste reduction, green job creation, and local resilience, can foster emotional connections and public enthusiasm (Hakovirta & Lucia, 2019). Digital platforms like YouTube, Instagram, TikTok, and children's books offer powerful tools for amplifying relatable stories and embedding CBS concepts into everyday life.

Finally, integrating stakeholder knowledge and local values into training materials ensures that CBS solutions are relevant across diverse communities. By prioritizing inclusivity in education, from K–18 learners to mid-career professionals, and providing multiple entry points into CBS careers, we will build a workforce capable of driving sustainable innovation at every level.

Investing in these strategies through the following grand research questions will empower communities to participate fully in the circular bioeconomy transition:

- How can multilevel education and training programs be designed to effectively raise awareness of CBS careers and equip learners with both foundational knowledge and practical skills required for emerging roles in the circular bioeconomy?
- What models of public–private partnership most effectively align academic curricula with industry needs in the circular bioeconomy while ensuring long-term program sustainability?
- Which outreach strategies best foster community engagement and social acceptance of CBS innovation, and how do these strategies influence workforce participation rates?

ADVANCING INNOVATION: SUCCESS STORIES AND FEATURED PROJECTS IN SUSTAINABLE DEVELOPMENT

Funding the Goals

Several federal agencies, such as USDA, NSF, and DOE, along with foundations like Schmidt Sciences, offer programs that support research and educational and outreach initiatives aimed at addressing the challenges outlined in this document. Additionally, some existing programs could be leveraged to support CBS innovations. For example, land-grant universities conduct 70 percent of publicly funded U.S. agricultural research and receive $265 million in annual Hatch funds, of which 25 percent ($66 million) support multi-state collaborations. Extensive resources including demonstration projects, pilot plants, and test sites position these institutions to catalyze multidisciplinary, multi-state use-inspired research and innovation. This will facilitate the transition from proof-of-concept projects to widespread adoption.

Together, these innovations and research priorities serve as a guiding framework for advancing a robust and resilient circular bioeconomy. The transition to a circular bioeconomy presents a rapidly growing opportunity poised to attract substantial funding and investment in the near future. By fostering a collaborative environment, we are well positioned to develop essential technologies and innovations, conduct groundbreaking research, develop standardized circularity metrics, engage our communities, and cultivate the skilled workforce needed to drive this transformation. Our long-term vision is to catalyze a comprehensive shift in supply chain systems, promoting a CBS mindset dedicated to delivering lasting benefits for communities, the economy, and future generations. The CBS conference participants returned to their institutions with renewed energy and a shared understanding that CBS implementation must be tailored to context, region-by-region, bioresource-by-bioresource, and stakeholder-by-stakeholder. Embracing this inherent complexity and diversity is key to advancing the circular bioeconomy effectively.

University of Georgia

The University of Georgia College of Agricultural and Environmental Sciences (CAES) launched the Circular Bioeconomy Systems (CBS) Initiative in January 2025 to drive Georgia's shift toward a circular bioeconomy. By unifying multidisciplinary teams and forging partnerships with regional universities, the initiative targets practical, zero-waste solutions for food security and sustainability. The recently opened Grand Farm innovation center in Perry, Georgia, will enable rapid prototyping and scaling up of developed circular technologies, positioning CAES as a leader in advancing resilient and sustainable bioeconomy systems for Georgia and beyond.

University of Tennessee Knoxville

The University of Tennessee-Oak Ridge National Laboratory CBS Convergent Research Initiative (CRI) is bringing together multiple disciplines to grow biobased solutions in local industries. The CRI was launched in 2024 to advance CBS by developing recyclable fuels, materials, and chemicals from renewable carbon sources. Leveraging expertise from both institutions, the CRI serves as a testbed for Tennessee's auto manufacturing and agriculture/forestry sectors, with multidisciplinary researchers collaborating in shared lab spaces to drive innovation and address CBS challenges statewide and beyond.

Virginia Tech

Virginia Tech's Office of Research and Innovation has launched the Ag Biotech and the Circular Bioeconomy initiative, bringing together multidisciplinary teams to tackle agricultural and food waste through academia-industry collaboration. Key innovations include creating biodegradable bioplastics from food waste, converting agricultural biomass into energy storage materials, and transforming seafood byproducts into high-value ingredients and biofuels. The initiative also advances workforce development by supporting the USDA National Needs Fellowship Program, preparing leaders to address food loss and waste, and driving sustainable solutions for a resilient circular bioeconomy.

North Carolina State University

North Carolina State University is pioneering a campus-wide circularity initiative: reducing, reusing, and exchanging resources across the university and the Research Triangle. Supported by Novo Nordisk and expanding biotech partners, NC State is mapping waste streams, recovering resources, and modeling circular strategies. These efforts lay the groundwork for a regional industrial symbiosis network, modeled after Denmark's Kalundborg Symbiosis, positioning NC State as the hub for a scalable, collaborative circular economy in North Carolina.

HudsonAlpha Institute for Biotechnology

The HudsonAlpha Institute for Biotechnology uses genomics research to improve human and plant health, spur entrepreneurship and economic development, and expand educational outreach to train future biotech leaders and build a biotech-literate public. Its plant research spans crops from peanuts to miscanthus. By unlocking the potential of agricultural crops, HudsonAlpha is helping create new income streams for farmers and rural communities while supporting a healthier planet through higher productivity, less waste, and renewable alternatives to petroleum-based materials.

BRIDGES NSF Innovation Engine

The BRIDGES Engine initiative, an NSF Innovation Engine finalist, seeks to advance perennial grasses like miscanthus as sustainable, bio-based alternatives to petroleum materials for the automotive, construction, and packaging sectors. By uniting academia and industry, BRIDGES is building a circular bioeconomy that strengthens rural communities, creates jobs, opens new markets for farmers, and boosts resilient supply chains through domestic feedstock production and manufacturing.

BIBLIOGRAPHY

ASABE. (2024). *Glossary and Definition of Terms*. https://cbsi-asabe.org/wp-content/uploads/2024/07/CBSI-Glossary-and-Definition-of-Terms.pdf

Baranwal, J., & Merino, D. (2025). Forefront Strategies for Biomass Valorization: From Deconstruction to Bioplastic Production. *ACS Materials Au, 5*(4), 610–631. https://doi.org/10.1021/acsmaterialsau.5c00023

Bringezu, S., Distelkamp, M., Lutz, C., Wimmer, F., Schaldach, R., Hennenberg, K. J., Böttcher, H., & Egenolf, V. (2021). Environmental and socioeconomic footprints of the German bioeconomy. *Nature Sustainability, 4*(9), 775–783. https://doi.org/10.1038/s41893-021-00725-3

Chennak, A.; Giannakas, K.; Awada, T. (2024). On the Economics of the Transition to a Circular Economy. *Circ.Econ.Sust. 4*(4), 3007–3023. https://doi.org/10.1007/s43615-023-00297-8

Circle Economy. (2025). *The Circularity Gap Report 2025*. https://pdf.circularity-gap.world/?report=CGR_Global_2025_Report_0c90048033&page=1

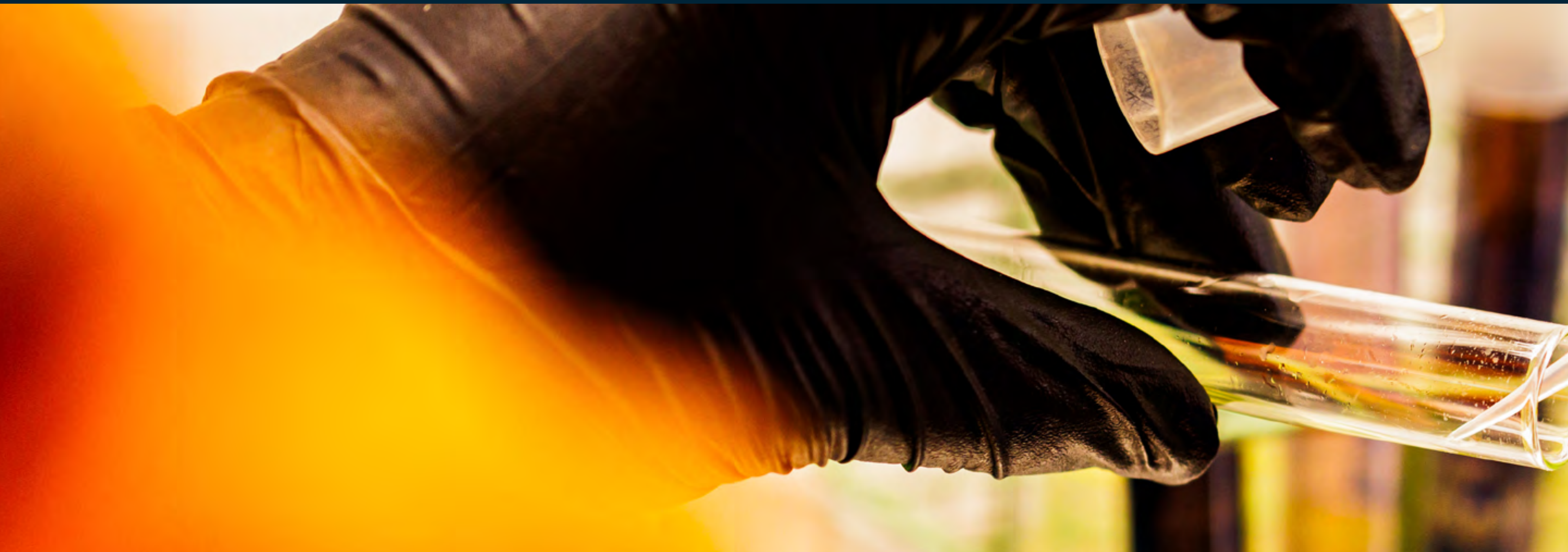
Dadi, M., Siwale, W., Munalula, F., Ravi, S. N., Mundike, J., Ramasamy, S., & Mulenga, C. (2025). A comprehensive review of advances in bioenergy including emerging trends and future directions. *Discover Energy, 5*(1). https://doi.org/10.1007/s43937-025-00095-3

El-Chichakli, B., von Braun, J., Lang, C., Barben, D., & Philp, J. (2016). Policy: Five cornerstones of a global bioeconomy. *Nature, 535*(7611), 221–223. https://doi.org/10.1038/535221a

Environment, The Japanese Ministry of. (2024). *The Sixth Basic Environment Plan*. https://www.env.go.jp/content/000288877.pdf

European Commission. (2018). *Sustainable & Circular Bioeconomy, the European Way – Outcome Report*. Edited by Burrows, D., DOI 10.2777/159097

Fullerton, D. (2025). The Circular Economy. In *Encyclopedia of Energy, Natural Resource, and Environmental Economics*; Elsevier, 254–265. https://doi.org/10.1016/B978-0-323-91013-2.00050-2



Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. *Journal of Industrial Ecology, 19*(5), 765–777. https://doi.org/https://doi.org/10.1111/jiec.12244

Hakovirta, M., & Lucia, L. (2019). Informal STEM education will accelerate the bioeconomy. *Nature Biotechnology, 37*(1), 103–104. https://doi.org/10.1038/nbt.4331

Langholtz, M. H., Brandt, C., Clark, R., Cook, H., Curran, S., Davis, M., De La Torre Ugarte, D., Efroymson, R., Field, J., Hellwinckel, C., Jacobson, R., Kline, K. L., Oyedeji, O., Parish, E., Schmidt, E., Theiss, T., Badgett, A., Klein, B., Milbrandt, A.,...Walker, L. (2024). *2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources.* https://www.osti.gov/biblio/2441098

The service-based bioeconomy. (2014). *Nature Biotechnology, 32*(7), 597–597. https://doi.org/10.1038/nbt.2961

U.S. Environmental Protection Agency. (2025, December 19). National overview: Facts and figures on materials, wastes and recycling. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials.

Watson, M. C., Rambhia, K. J., Seltzer, M. J., Carter, S. R., Moritz, R. L., Attal-Juncqua, A., Diggans, J., & Dileo, J. (2025). Toward a safer and more secure US bioeconomy. *Nature Biotechnology, 43*(1), 23–25. https://doi.org/10.1038/s41587-024-02519-2

Zhang, Y., Oates, L. G., Serate, J., Xie, D., Pohlmann, E., Bukhman, Y. V., Karlen, S. D., Young, M. K., Higbee, A., Eilert, D., Sanford, G. R., Piotrowski, J. S., Cavalier, D., Ralph, J., Coon, J. J., Sato, T. K., & Ong, R. G. (2018). Diverse lignocellulosic feedstocks can achieve high field-scale ethanol yields while providing flexibility for the biorefinery and landscape-level environmental benefits. *GCB Bioenergy, 10*(11), 825–840. https://doi.org/https://doi.org/10.1111/gcbb.12533

UTIA INSTITUTE OF AGRICULTURE
THE UNIVERSITY OF TENNESSEE
Real. Life. Solutions.™

06/26 26-0124