World without Waste

A Circular Bioeconomy

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UIDP
Strengthening University-Industry Partnerships

Workshop Report

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UIDP conducted this workshop on behalf of the NSF Biology Directorate to leverage top scientific minds to identify biotechnology research areas for strategic investments and acceleration.

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Executive Summary

Creating a future without waste or pollution is among society's most pressing challenges and greatest opportunities to improve the human condition. Achieving this goal in our lifetime requires rapid technological innovation, which can only be achieved when transformative discoveries from basic science and engineering research are translated to practice. Federal agencies such as the National Science Foundation (NSF) are coordinating efforts to develop partnerships to advance a circular bioeconomy. This workshop convened stakeholders from multiple sectors and disciplines to identify partnership strategies for use-inspired research that can be rapidly translated to advance an innovative, economical, and sustainable circular bioeconomy.

More than 100 participants from academic, industry (large and small), government, and nonprofit sectors convened virtually for two days in August 2021 to define priorities and enumerate the challenges for advancing the circular bioeconomy. The invited scientists and researchers were strategically selected to ensure that diverse perspectives and expertise were represented in the workshop deliberations.

Purpose of the Workshop

By and large, society's use of materials follows a straight pattern. In recent years, particular attention has centered on the linear nature of plastics as an environmental challenge. The high volume of waste at the end of the plastics lifecycle causes adverse environmental effects, and the direct system wastes the valuable carbon and energy that end-of-life plastics contain. Plastics represent just one linear material system; society loses a dramatic amount of metals when spent lithium-ion batteries and other electronics make their way to landfills, when storms sweep nutrients from farms into rivers, and when industrial waste like kraft liquor or sludge from wastewater plants is not tapped for the energy, materials, or nutrients within them. At the current rate of plastic waste generation, there will be more plastic (by weight) than fish in the ocean by 2050.[1]

Biological systems offer a dramatic opportunity to increase circularity in our material systems. However, the circular bioeconomy must overcome numerous challenges before it can be realized, which include:

- Barriers to development because of the complexity of these systems;
- High costs to economically scale up necessary bio-based solutions;
- Large knowledge gaps, including those in data and biological systems;
- Proven ability to economically compete with lower-cost, linear systems; and
- A severe lack of infrastructure for waste collection in many regions.

The workshop's goals were to define the needs for a zero-waste, circular bioeconomy, identify gaps to progress, and articulate short- and long-term goals to achieve successful outcomes. Use-inspired research should be directly connected with and lead to innovations that translate knowledge into practical outcomes. Established partnerships among all sectors (public, private, nonprofit) are essential for achieving these common goals and, thus, inherent to success. Industry-academic research consortia are one example of the kind of partnership that will contribute to developing the circular bioeconomy. Both those participating in the research and those investing in it will benefit from collaborative R&D efforts.

Workshop Findings in Brief

Steps to Address Areas of Concern

- Assess technologies early in the development cycle and account for how they fit with existing materials infrastructure.
- Collaborate with social scientists on messaging that is tailored to unique audiences.
- Design and produce circular bioeconomy products with market pull and with a life-cycle mindset.
- Develop industry-university collaborations with streamlined intellectual property and funding models targeted toward increasing scale-up successes.
- Engage the myriad diverse stakeholders earlier and more frequently (both the general public and across the value chain) in product, process, and systems development.
- Explore emerging employment opportunities through the realization of the circular bioeconomy.
- Enable cross-region fundamental science sharing while adopting customized local approaches.

Necessary Technical Advances

- Address challenges in the scale up of biological systems.
- Create and sustain pre-competitive common spaces that enable data sharing to address common challenges technology developers face.
- Determine the performance advantages of strategies for basing the circular bioeconomy on small chemical building blocks versus unique but complex bio-derived compounds.
- Develop low-cost conversion technologies that use low-cost feedstocks and are supported by a strong business case for competition with low-cost incumbent materials and processes.
- Develop robust waste management and sorting technologies that can operate cost-effectively in distributed environments.
- Develop technology that uses microbes to break down complex end-of-life materials into high-quality components that can be reused.
- Employ life cycle assessment, technoeconomic analysis, and material flow analysis to shed light on the space between infinite circularity and today's linear systems.
- Expand priorities for circularity beyond carbon to emphasize nitrogen, phosphorous, and even waste heat and byproducts in bioprocesses.
- Expand the knowledge base that underpins the circular bioeconomy from the fine scale (atom, enzyme, microbe) to the systems scale (waste collection infrastructure, product and process design).
- Explore universal, scalable and cost-effective strategies to effectively incorporate biobased content into synthetic materials.
- Evaluate the appropriateness of different technologies for modular distributed approaches, as opposed to the centralized approaches on a regional basis that account for feedstock availability.
- Identify new material paradigms for overcoming the limitations of biobased materials in high-performance applications, for example, low fire-tolerance, low hydrophobicity, and long-term durability.
- Improve the fundamental science that informs our understanding of non-ideal, ecologically robust biological systems.
- Leverage biology, chemistry, and hybrid approaches to improve recycling processes.
- Produce models that improve understanding of circular, biobased materials at multiple scales.
- Produce and maintain inventories of biomass and wastes globally to inform economically viable feedstocks that are regionally available.
- Understand how to separate synthetic and biobased components from materials into waste streams that can be independently processed or valorized in an energy-efficient way.
- Improve the scientific understanding of microbial signaling.

Key Findings: Participants discussed specific questions and focused on key topics in biological systems design, sustainable biosourced materials and products, biomanufacturing, enabling circularity, regional and international approaches, innovation recipes and collaboration, public engagement, and reducing risk. The need to address societal aspects of the circular bioeconomy was also a consistent theme throughout the workshop. These discussions produced specific recommendations for research and collaboration activities which are described below:

» **Build data repositories on shared, transparent, and consistent platforms.** Shared data resources pertaining to material properties (of recycled and/or bio-based materials), biological systems and their behavior, and other common components of a circular bioeconomy will help remove barriers to technology development.

» **Characterize regional differences** in feedstocks, waste generation types, amounts, and distribution, along with societal approaches to waste management, to build successful regional approaches to a circular bioeconomy.

» **Design biological processes holistically from the outset**, with clear goals accounting for biological components' tolerance of processing conditions.

» **Develop quantitative definitions and targets** for the circular bioeconomy to mobilize efforts toward common goals.

» **Devise successful strategies for biological processes and manufacturing scale up** given their unique and complex nature.

» **Expand scientific knowledge to capture data** reflecting the complexity and non-ideality of biological systems.

Participants identified **overarching knowledge gaps for additional research**, to include the need for:

- **Clear focus on short-term scalable processes** that can utilize existing infrastructure to enable quick wins both from an economic and sustainability standpoint;
- **Clearly identified strategies and business models** to enhance the waste handling infrastructure in the United States; and
- **Consensus, as well as consistent standards and definitions**, for product features critical to a circular bioeconomy, such as "biodegradability;"
- Data and data sharing infrastructure for the circular bioeconomy.

Recommendations and Next Steps

Achieving the goal of a circular bioeconomy requires consensus in the scientific and policy communities and commitment at a high level to:

- **Develop a framework** to steer circular bioeconomy research and collaboration efforts in a consistent direction based on economic viability, environmental and societal sustainability;
- **Develop an entrepreneurial, circular bioeconomy workforce**; and
- **Identify best practices in developing partnerships** among suppliers and end-product manufacturers (e.g., from the electronics industry).

This report summarizes the key insights from the workshop and is not intended to be a detailed record of the entire proceedings. We encourage you to share this document with interested parties.

Introduction

Historically, the world's economy has been undeviating. In this system, raw materials and resources are used to make products, and then the products are used and thrown away, creating a take-make-use-waste process. Consider plastic packaging as an example – about 80 million metric tons of plastic packaging is produced in the world annually. Only 14% of it is collected and recycled, with only 2% contained in a closed-loop process. Over 50% of it either is incinerated or goes to landfills, and a significant amount leaks into the environment.[2] Like plastics, other systems are also highly linear and produce significant waste. For example, about 50 million metric tons of electronic waste are generated annually worldwide; 80% of such devices are not collected at the end of their useful life.[3] Finally, of the about 60 million metric tons of food waste generated in the United States annually, only 32% is recycled and reused.[4]

The goal of the workshop was to convene stakeholders from multiple sectors and disciplines to design a future of circular bioeconomy that is innovative, economical, and sustainable. Workshop participants represented industry, academia, government, and non-profit organizations and focused primarily on opportunities and challenges for a circular materials bioeconomy. They identified barriers and opportunities to advance the circular economy in technical areas, including developing fundamental biological systems understanding, designing biomanufacturing processes, using bio-derived feedstocks to produce value-added materials, and addressing elements of a circular economy, such as distributed recycling infrastructure, which are lacking today. Participants also discussed new collaboration modes necessary to accelerate progress toward a circular economy. One example of critical collaborations is between industry and academia, which is essential to ensure that the ideas created on campus are appropriately developed and enter the market and advance society toward the circular bioeconomy and a world without waste.

Level-Setting: Challenges and Roadblocks

A pre-event survey was distributed to participants prior to the workshop to identify key opportunities related to supporting the circular bioeconomy. Using a scale of 1 (not important) to 5 (very important), these rankings were condensed into weighted averages. The survey questions corresponded to the four themes discussed in the workshop breakout sessions: Biological Systems Design, Sustainable Biosourced Materials and Products, Biomanufacturing, and Enabling Circularity.

Biological Systems Design. Participants ranked *Microbial community behaviors in processes that convert wastes and/or biomass to desired products* as the area of highest importance with a weighted average of 4.0, followed by *Microbial diversity* with a weighted average of 3.75.

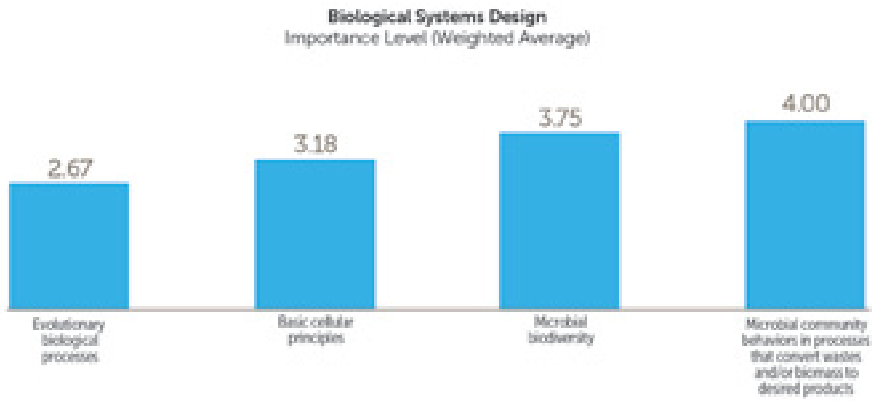


Figure 1 | Survey results on the importance for industry and academia to collaboratively expand knowledge and remove barriers to biological systems design as it relates to achieving a circular bioeconomy. Participants scored level of importance on a scale of 1 ("Not important") to 5 ("Very important"). Numbers above bars represent the weighted average across *n*=13.

Sustainable Biosourced Materials and Products. Participant ranking was split more evenly for *Sustainable agriculture and Feedstock (biomass, wastes) supply chain development* ranked at the top with weighted averages of 4.38 and 4.33 respectively. The high importance of sustainable feedstocks and feedstock processing was a common theme that emerged among participants in the pre-event survey and elsewhere during the workshop. It is worth noting that all elements were rated higher than 3.4 out of 5.

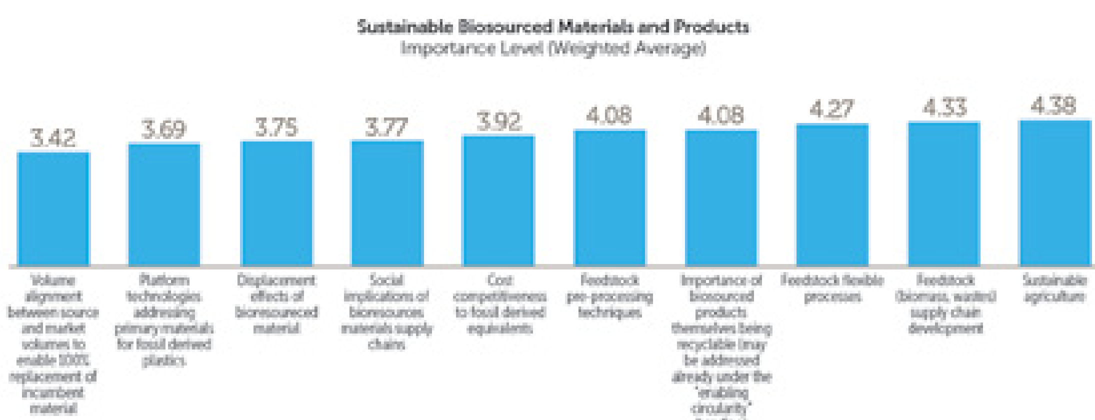


Figure 2 | Survey results on the importance for industry and academia to collaboratively expand knowledge and remove barriers to sustainable biosourced materials and products as it relates to achieving a circular bioeconomy. Participants scored level of importance on a scale of 1 ("Not important") to 5 ("Very important"). Numbers above bars represent the weighted average across *n*=13.

Biomanufacturing. *Development of new manufacturing paradigms that leverage waste and biomass feedstocks* was rated highest, with a weighted average ranking of 4.54; this priority was underscored during the workshop among participants. Although participants ranked *Development of robust conversion processes for different feedstock types (including process efficiency)* and *Addressing challenges in translation such as process efficiency, understanding and mitigating impact of raw material differences, reducing cost, creating transparency in assessing carbon impact* as relatively less important (4.31 and 4.15 weighted averages, respectively), these two topics are still ranked as very important in absolute terms.

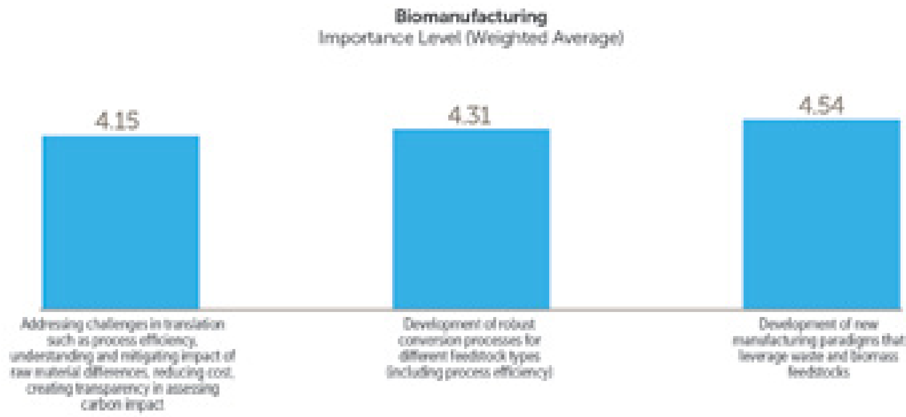


Figure 3 | Survey results on the importance for industry and academia to collaboratively expand knowledge and remove barriers to biomanufacturing as it relates to achieving a circular bioeconomy. Participants scored level of importance on a scale of 1 ("Not important") to 5 ("Very important"). Numbers above bars represent the weighted average across *n*=13.

Enabling Circularity. Participants selected *Design of materials that are inherently recyclable and degradable to benign products* as most important, closely followed by *Insights into how a circular bioeconomy might vary regionally* (4.38 and 4.25 weighted averages, respectively). Although not ranked as high, the effect on disadvantaged groups, the need to develop an analytical evaluation framework, and the training of scientists and engineers were also shown to be very important. Participants indicated that they view social/cultural components to be almost as important as technological advances in terms of achieving a circular bioeconomy.

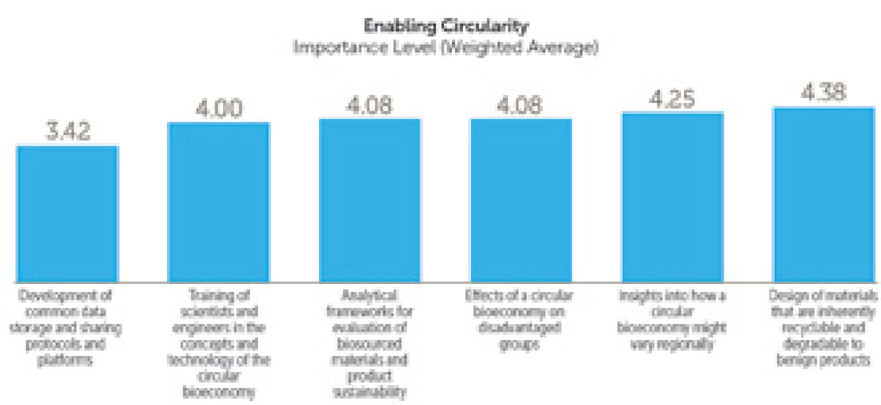


Figure 4 | Survey results on the importance for industry and academia to collaboratively expand knowledge and remove barriers to enabling circularity as it relates to achieving a circular bioeconomy. Participants scored level of importance on a scale of 1 ("Not important") to 5 ("Very important"). Numbers above bars represent the weighted average across *n*=13.

Conclusions from the Research Landscape

UIDP and NSF worked in partnership with Elsevier to perform a review of the global circular bioeconomy's R&D landscape.[5] Over the past 20 years, research focused on the goal of a World Without Waste through a circular bioeconomy has grown internationally at a rapid pace (Figure 5). Between 2001 and 2020, over 300,000 research papers that focused on this goal were published. During this time, the global research output in this area grew at a compound annual growth rate of 11.4%, outpacing the compound annual growth rate of the overall global research output by almost six percentage points. While the United States and China published the most research on a circular bioeconomy, India, Brazil, and Spain dedicated a higher percentage of their research portfolio to the topic (1.2-1.3% of each country's research portfolio), indicating the high priority status of this research in those countries. Looking at both the 20-year period and especially the last five years, research in a circular bioeconomy appears to be especially important in developing economies and middle-income countries. India is quickly catching up to the United States in terms of annual publication output.

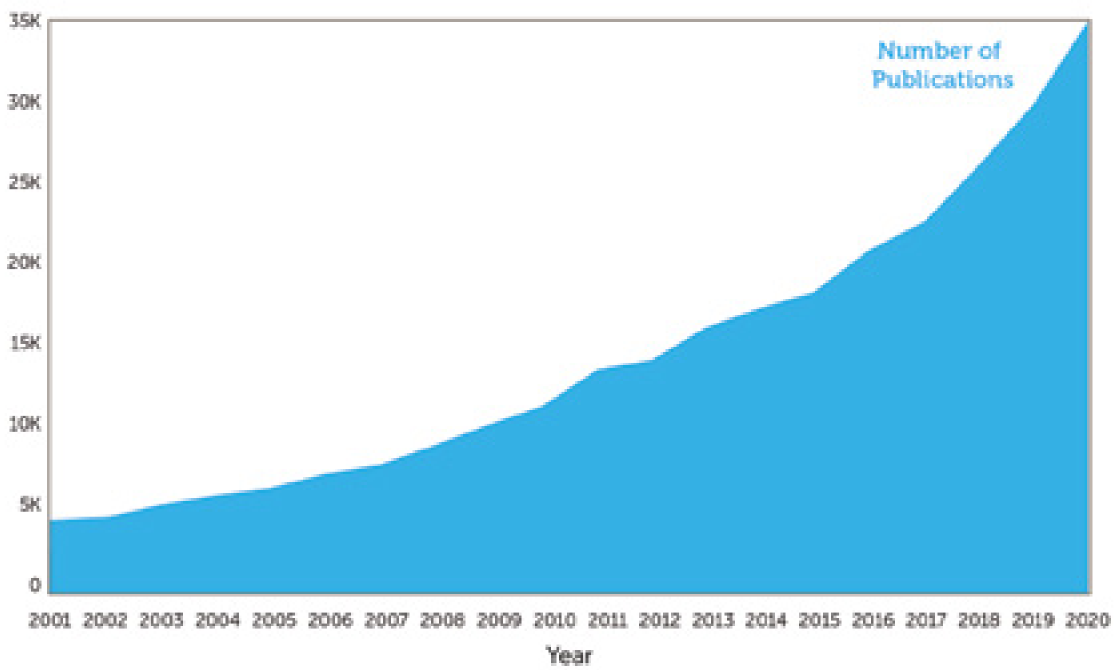


Figure 5 | Number of publications on a circular bioeconomy, 2001-2020.Source: Scopus

Research in this area spans a wide spectrum of fields, from environmental science, energy, chemical engineering, to agriculture and biological sciences. In the United States, the research extends across several sectors, with federal government institutions conducting the most research. The Department of Agriculture has contributed the most to U.S. circular bioeconomy literature over the last 20 years, and the Department of Energy has emerged as a major contributor over the last decade.

In the United States, clusters of research topics, such as microbial fuel cells, anaerobic digestion, and bioreactors, are highly represented within the corpus of research on a circular bioeconomy. Studies on this cluster exhibited an average year-over-year growth rate of 8% between 2016 and 2020. Additionally, research in these topic clusters was published by a diverse group of researchers, including a substantial number of contributions from corporate institutions (in collaboration with academic institutions). Together, these findings demonstrate the diversity of players, disciplines, and topics in research on a World Without Waste through a circular bioeconomy.

This growth in circular bioeconomy publication output has been driven by continued focus on the research area from the United States and European countries, as well as a rapid increase in publications from China and India (Figure 6). These data show that China published the most circular bioeconomy research, producing 62,115 publications during the period 2001-2020, with particularly high growth over the last four years of the period (2016-2020). The United States and India followed with 49,771 and 24,166 publications during the period, respectively. Several of the current European Union member states (EU 27) were also among the top countries publishing on circular bioeconomy and collectively surpassed the United States and China with a publication output of 94,000. Despite this high output by both the United States and China, other countries, such as India, Brazil, and Spain, dedicated more of their overall research efforts to this area. Circular bioeconomy publications by these countries represented 1.2-1.3% of their national research output compared to 0.5% of total U.S. research output related to circular bioeconomy. Publication output trends indicate that this research area has high interest from both established and emerging research countries and jurisdictions and appears to be especially important for developing economies and middle-income countries.

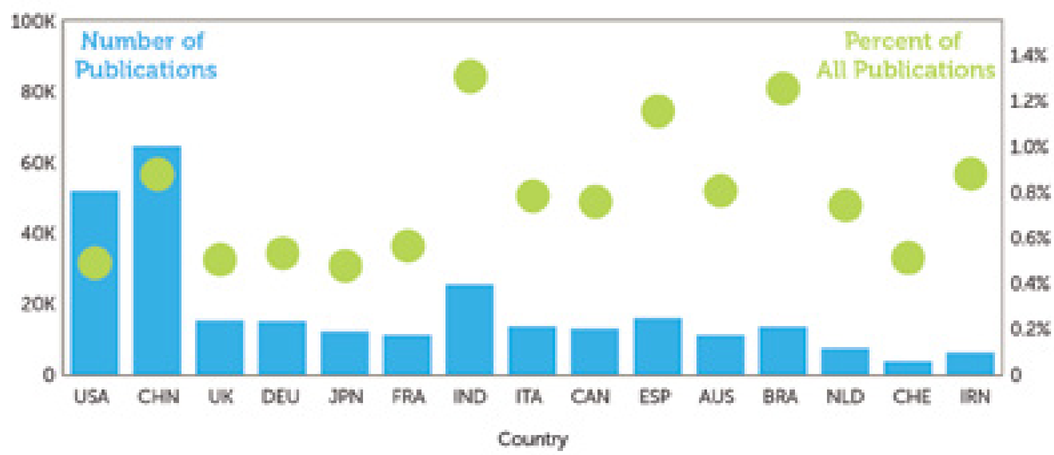


Figure 6 | Number of research publications on this topic and percent of the regional research portfolio represented by circular bioeconomy research, 2001-2020. Source: Scopus

Key Takeaways

- Between 2001 and 2020, over 300,000 research papers on waste reduction through a circular bioeconomy were published.
- Research in this area spans a wide spectrum of fields, including environmental science, energy, chemical engineering, and agriculture and biological sciences.
- During 2001-2020, the global research output in this topic area grew at a compound annual growth rate of 11.4%, outpacing the compound annual growth rate of overall global research output by almost six percentage points.

Increased circular bioeconomy publication output has been driven by continued focus on the research area from the United States and European countries, as well as a rapid increase in publications from China and India.

Session Highlights from Day 1: Defining the Circular Bioeconomy

The first day of the workshop focused on defining the key barriers to a world without waste, describing the available state-of-the-art technologies and identifying the remaining gaps in knowledge. After participants discussed the workshop charge, they were placed into four breakout groups and asked to address the following four questions as they related to the group topic:

1. What do we define as a zero-waste, circular bioeconomy?
2. What are the research questions and outcomes needed to get to a zero-waste, circular bioeconomy?
3. What is the current state of progress toward commercial implementation of the circular bioeconomy and technology transfer?
4. What are the barriers to translation of new research and adoption in the marketplace?

Facilitated Breakout Sessions

Biological Systems Design

This breakout session explored the expansion of natural biological systems knowledge across all scales of life and leveraging this knowledge in design. Attendees discussed gaps in understanding of biotechnology innovation, synthetic biology tools, biodiversity, and environmental science.

Key Takeaways

Tackle the complexity and non-ideality in biological systems. At multiple scales (enzymes, microbial communities, biological processes to make or recycle materials), the understanding of biological systems in real-world conditions is limited. Research efforts should expand beyond model organisms to encompass synthetic microbial communities, algae, and fungi under non-ideal conditions that include potential contaminants and decomposition products that impede performance. As a whole, there is a need to develop microbes and communities with better ecological fitness. Regulatory testing of new microbial systems or the use of existing systems in new environments will require careful review to address the potentially competing objectives of safety and speed.

Design biological systems using a holistic view of circularity. Priorities for circularity should expand beyond carbon to emphasize nitrogen, phosphorous, and even waste heat and byproducts in bioprocesses. To advance circularity related to nitrogen, additional data are needed regarding the transport and fate of nitrogen in the environment and how landscape engineering, fertilizer application rates, plant-microbe interactions, and climate affect our ability to reclaim nitrogen into circular systems.

Address challenges in the scale-up of biological systems. As research delves into more complex systems, the time between bench-scale breakthroughs and commercialization may lengthen as results generated with model systems are translated to non-model systems. Machine learning and modeling approaches should be explored for their potential to accelerate this timescale. Furthermore, the foundational characteristics of rate and yield that are core drivers of processing cost must be considered as new processes are developed. While much emphasis is placed on plastic recycling, microbial communities have the potential to break down many types of complex end-of-life materials, including electronics. However, these processes are not well characterized, especially at larger scales. Signaling (regulation at scale) also merits increased research.

Sustainable Biosourced Materials and Products

This session focused on economically competitive and sustainable biosourced materials, including methods to process them in environmentally benign ways. The discussion included approaches to design products with end-of-life properties that enable reuse or recycling, thereby actively contributing to the foundation of a circular bioeconomy.

Key Takeaways

Develop a sustainable circularity framework. Defining a world without waste is challenging because it encompasses atom-level recovery and recycling as well as system-level end-of-life strategies to minimize waste. Yet, quantitative definitions and targets are essential to mobilize industry, academia, government, and consumers toward a circular bioeconomy. Frameworks for evaluating systems-level sustainability of biosourced materials and products are therefore essential. These frameworks, including life cycle assessment, should enable consistent comparison and use recurring definitions for terms, such as biodegradable and microplastics. These frameworks must incorporate economic viability.

Establish data and physical infrastructure. Lack of infrastructure and logistics for waste handling is a significant barrier to the circular bioeconomy. Using biosourced materials requires collection and separation of waste products (e.g., agricultural and post-consumer) into usable streams. Feedstock reliability may decline as production systems shift to recycled or bio-based feedstocks. The potential to use these feedstocks in simple, existing infrastructure (such as crackers) could accelerate the transition to a circular bioeconomy but risks reliance on captured capital and could limit innovation. Data sharing across the value chain, including that pertaining to available infrastructure, is a critical part of the circular bioeconomy. Data and physical infrastructure needs should be catalogued and addressed on a regional basis to highlight opportunities for investment and collaboration. There is an opportunity to pilot new approaches to infrastructure that could advance the circular bioeconomy.

Design and manufacture products with market pull. Biosourced materials and products must go beyond cost-competitiveness and exhibit high performance during their lifetimes, yet also be poised for re-entry into a circular system at end-of-life. Regardless of the original material, this requires improved integration of capabilities (such as debonding on demand) that enable circularity. Designing for recyclability is essential; engineers and scientists must be trained to consider end-of-life factors at the very beginning of a product's design life cycle. Producing biobased materials from simple molecules could be one way to proceed, such as from carbon dioxide or cellulose. Research at the university-industry interface should explore performance metrics and properties (including at end-of-life) that would render biosourced materials a consumer favorite and develop routes to producing these products with new feedstocks and processes.

Biomanufacturing

Novel manufacturing infrastructure processes, distributed manufacturing models, process intensification, and real-time characterization and control methods are all important aspects in the development of biomanufacturing.

Key Takeaways

Develop technologies with integrated systems design in mind. Considering feedstock properties, downstream processing, use, and waste management when designing a system is important. For example, researchers should develop organisms with the performance requirements needed in the processes that will incorporate them. The potential for feedstock flexibility should be evaluated.

Assess technologies early in the development cycle. Consider performing early-stage assessment (e.g., techno-economic analysis and life cycle assessment) to provide an early judgment of process feasibility and insight into how to steer technology development toward that aim. This could be accomplished through targeting research efforts based on advances needed to reduce costs or enhance sustainability.

Consider materials infrastructure and scaling. When designing new materials, it is critical to account for compatibility with the existing infrastructure. Modifying existing, largely distributed infrastructures or building new infrastructures for new materials can be expensive. Industry, in collaboration with academia and other research performers, must be at the forefront for determining the feasibility of scaling and forecast potential scaling issues when designing new materials. To decrease risk, underlying scaling problems should be identified so more predictable and feasible technology can be developed.

Enabling Circularity

Topics discussed in this group included: data and computing infrastructure; societal, environmental, and economic factors; and strong community engagement and workforce development..

Key Takeaways

Develop definitions and targets. Complete circularity is unreachable given that material property degradation and some leakage occur within circular systems. While upcycling, downcycling, and recycling are often prioritized over composting materials to enable reclamation of nutrients or carbon, composting may play an important role in reducing waste and enabling the circular bioeconomy and should be evaluated alongside other options for material reuse. The need for a consistent, quantitative, transparent, and defensible definition of circularity that is widely accepted is clear. Circular bioeconomy definitions should include quantitative targets based on life cycle assessments, material flow analyses, and economic evaluations.

Adopt data-informed strategies. One potential approach is to recreate today's plastics numbers 1-7 using bio-based sources. Alternatively, it may be desirable to produce new materials that have favorable properties or performance, including enhanced recyclability, degradability, and compostability. Evaluating these options and their implications throughout plastics' life cycle will help guide research and development and requires data that is currently unavailable. These include physical properties (e.g., viscosity) of materials (waste and upcycled, downcycled, or recycled), as well as detailed chemistry information (e.g., kinetics, heat demand) of processes that enable upcycling, downcycling, or recycling. Sharing data in a pre-competitive format among academic, industrial, and other stakeholders will accelerate progress. Furthermore, new analytical tools may be required to generate the necessary data.

Address societal aspects of the circular bioeconomy. Researchers face knowledge gaps regarding societal and regional opportunities, limitations, and challenges to developing a circular bioeconomy. Societal aspects of the circular economy are often overlooked. As materials evolve to enable circularity, consumers may need to adapt to different material look, feel, and performance. Similarly, producers may need to anticipate how new materials might affect consumer behavior and design their products in consideration of the behaviors that make circularity straightforward and easy. Corresponding behavior changes could either complicate or accelerate progress toward circularity. Business models that place end-of-life responsibility in the hands of producers versus consumers may be worth exploring to influence behaviors that enable circularity. Finally, laying the path toward a just transition to a circular bioeconomy merits attention.

Closed Loop Partners > Hannah Friedman, Investment Associate, Closed Loop Partners

Background

Founded in 2014, Closed Loop Partners is a New York-based investment firm that provides equity and project finance to scale products, services, and infrastructure at the forefront of the development of the circular economy.

Business Model

Closed Loop Partners has an **innovation center** that executes research, analysis, and pre-competitive collaborations to accelerate the transition to a circular economy in which materials are shared, re-used, and continuously cycled. The firm also has **four investment platforms** that build upon one another, bridging gaps and fostering synergies to scale the circular economy:

- **Infrastructure group:** Financing recycling circular economy infrastructure across North America..
- **Ventures group:** Investing in companies across the food and agriculture sector, strengthening every stage of the value chain.
- **Growth equity group:** Investing capital in innovative companies to deliver the scalable solutions necessary for a more circular future for the global fashion industry.
- **Private equity group:** Acquiring companies along the value chain to build circular supply chains.
- Across the business model, the firm focuses on four sectors: plastics and packaging, supply chain technology, food and agriculture, and fashion.

Navigating Plastic Alternatives in a Circular Economy

With the demand for a circular economy of plastics, many companies are turning to bio-based plastics, biopolymers, and compostable alternatives, resulting in a flood of new materials entering the market as plastic alternatives. However, there is not enough recovery infrastructure to recapture their full value efficiently. The misalignment between production and end-of-life demonstrates a critical need to ensure that higher volumes of plastic alternatives (e.g., compostable packaging) do not end up in landfills in the future.[6] Closed Loop Partners developed the following approach to address the issue:

- **Understand:** Know the nuances of plastic alternatives, including biopolymers, in the context of a broader suite of solutions required to address plastic waste.
- **Invest:** Catalyze capital to scale the organics processing infrastructure necessary to recover the increasing volume of compostable products and packaging.
- **Collaborate:** Align product design, materiality, infrastructure capacity, incentives, and labelling standards to ensure that plastic alternatives drive value across the system.

Three key takeaways from navigating plastic alternatives were presented:

- **Reduce contamination through labelling.** Labeling materials to differentiate between recyclable and compostable materials to ensure they end up in the right places is key.
- **Drive value to recycling and composting systems.** For recycling, driving value is contingent upon keeping streams clean, design innovation to keep materials recyclable, and then pushing materials through the recycling system. For composting, the key is diverting food scraps to composter infrastructures. Highly contaminated food packaging can push more food scraps into the composting system.
- **Avoid externalities through testing.** Testing in both post-customer and production stages is critical to avoid negative externalities. Testing at the end-of-life can avoid depositing recyclable or compostable materials in landfills or leaking into the environment. Testing on the production side can prevent toxicities in new materials.

Session Highlights from Day 2: Accelerating the Research

The group's conversations and conclusions from Day 1 were translated on Day 2 into how to accelerate solutions within 2-, 5-, and 10-year timeframes. Toward this goal, the following questions were posed to attendees, which were then discussed as they relate to the breakout topics:

1. Where are the most compelling opportunities?
2. How can innovation and discovery be accelerated in this area?
3. How can solutions be implemented on a global scale?
4. Who are the major stakeholders?
5. How can the public be engaged early in the process?
6. How will opposing viewpoints be engaged and accommodated?
7. How can opportunities and benefits be equitably distributed?
8. What are the regional considerations to be made, including coastal/island territories?

Facilitated Breakout Sessions

Regional and International Approaches

Regions (domestically and internationally) differ in their variety of bio-based feedstocks, industrial makeup, supply chains, and markets. This uniqueness can be leveraged to inspire innovation in different regions, enabling near-term impact on the circular bioeconomy. This discussion sought to evaluate and learn from current stakeholders and the experiences of workshop representatives from other nations, namely in the European Union and United Kingdom, and identify routes for building and maintaining national prominence in the elements and implementation of the circular bioeconomy.

Key Takeaways

Enable cross-region fundamental science sharing. Fundamental science and data should be shared to support regional technology development. For example, researchers should publish detailed information about the microorganisms they develop for application in a circular economy or physical properties of materials as they iterate through multiple use cycles, potentially in different applications. Open data hubs with well-defined standards should become the norm. One example of this is the NSF-supported Big Data Innovation Hubs that encompass four geographic regions (West Big Data Innovation Hub, Midwest Big Data Hub, South Big Data Hub, and Northeast Big Data innovation Hub).[7]

Adopt customized local approaches. Regional efforts should start with conversations that explore community needs and co-designed approaches using cost-effective, adaptive resources that relate to regional technology capabilities and feedstocks/wastes. Efforts should develop data and information to inform regional approaches, including those pertaining to social, economic, and environmental factors. Workforce development should also be customized to align with local factors.

Communicate across the value chain and disciplines. The circular bioeconomy is highly interdisciplinary and multifaceted, which requires communication among federal, state, and local agencies, academic disciplines, and stakeholders, including end-product customers. For example, it is essential to engage with agricultural groups and government entities to identify champions willing to pilot waste collection efforts on farms or in communities. These conversations will identify regional barriers and opportunities to the circular bioeconomy that could be addressed through data sharing, research, and application of existing technologies in novel environments. Finally, the circular bioeconomy requires communication and meaningful engagement between science and engineering disciplines and the social sciences, which hold critical insights into human behavior.

Innovation Design and Collaboration

Optimizing design strategies that include fundamental science, use-inspired research, and high-risk research will result in a continuous cycle of scientific advances that accelerate the circular bioeconomy. Identifying the optimal roles and leveraging the unique abilities of each stakeholder–including academia, industry, start-up organizations, foundations, NGOs, and government agencies–can support the realization of the circular bioeconomy.

Key Takeaways

Build new collaboration models. The circular economy is a grand challenge that must be addressed with an all-hands, global approach. Collectively, the research community needs to develop better, more efficient ways for industry, academia, national laboratories, and other stakeholders to collaborate. Streamlined models to fund research, such as the United Kingdom's CASE program, should be explored.[8] Given the risks associated with process scaling, the community should explore opportunities for government, industry, and academia to take a stepwise approach that distributes scaling risk. Another collaborative activity should be developing an entrepreneurial workforce.

Modify intellectual property (IP) models. Limiting access to intellectual property and use of traditional technology transfer management approaches can impede discovery. Broader adoption of new IP approaches that reduce collaboration barriers between universities and companies (and others) will accelerate the development of new processes, products, and services. Furthermore, intellectual property management and protection costs can be challenging for many institutions and small companies.

Build pre-competitive common spaces. Pre-competitive commons that contain valuable data, models, and concepts can create markets and value. For example, the iGEM repository[9] is a dominant pre-competitive space in biotech; more spaces like this should be built. Consortia-based approaches in which government agencies convene the research community to select and build investment-worthy, pre-competitive spaces could be ideal.

Public Engagement

Public engagement and acceptance are essential to move from a linear, fossil fuel-based economy to one built on circular approaches that leverage renewable resources. Since the circular bioeconomy challenge is global in character, building global public interest in and support of the bioeconomy is critical.

Key Takeaways

Tailor communication approaches for different individuals/groups. Outreach efforts should focus on the knowledge of those individuals/groups so the education and dialogue are tailored appropriately. For example, for younger groups, engaging a trusted influencer (through social media) may be more effective than relying on conventional marketing.

Collaborate with social scientists to engage with consumers. Strategies and insights from leading social and behavioral experts should be incorporated to craft messages that will effectively deliver information about the circular bioeconomy while minimizing unintended consequences (e.g., fear of unknown aspects, such as new technology/material). Furthermore, applying social science from a range of disciplines (including anthropology, communications, and economics) to better understand the perception and impact of "greenwashing" may be essential to deliver effective messages.

Adopt a comprehensive approach to communicate circularity's benefits. Consumers have wide-ranging concerns, from social justice, wellness, to quality of life, which should be addressed during public engagement. Lessons learned based on previous success stories of public engagement that incorporated this type of holistic thinking, such as successes in building the consumer base for organic foods, should be explored and leveraged.

Session Reducing Risk

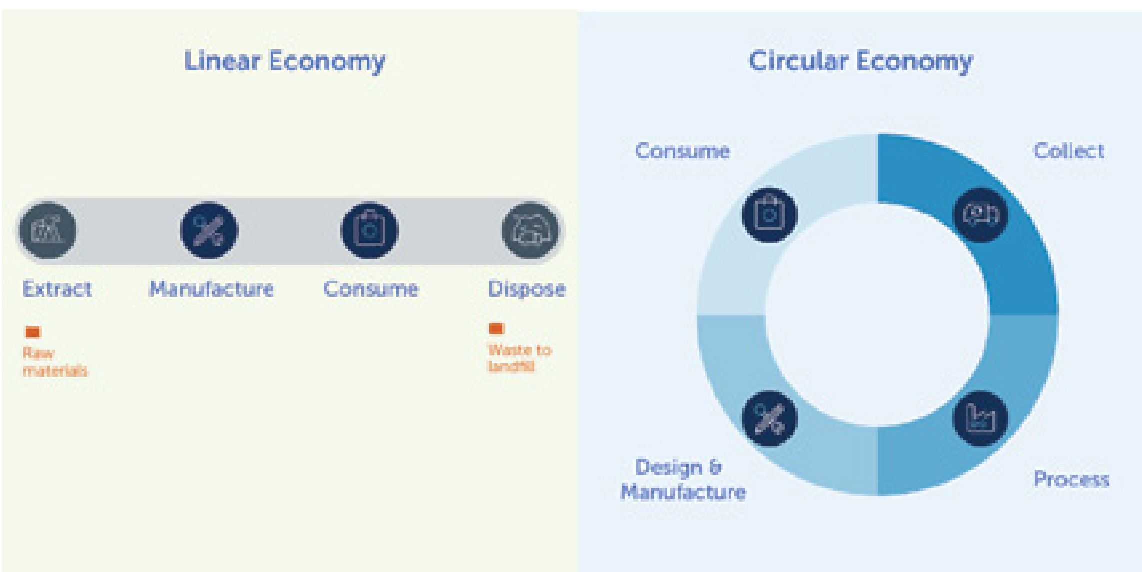
Participants evaluated technologies that are market-ready in the near- and long-term. They reviewed the community of stakeholders involved in the reduction of risks and barriers toward realization of technology commercialization. Finally, they identified critical barriers to near-term adoption and implementation of technologies to enable the circular bioeconomy and how stakeholders can contribute to and benefit from overcoming those barriers.

Key Takeaways

Reduce feedstock-associated risks. Bio-based feedstocks differ in type, composition, and availability by region. Accordingly, there is a need for feedstock characterization data that will guide processing and target product decisions. Regional approaches that use local feedstocks limit supply chain disruption risks but may increase risks associated with feedstock complexity or regional integration with national systems. They may require decentralized conversion or recycling technologies that leverage the diverse abilities of biological systems. Notably, waste-derived feedstock supply may tighten as demand increases. Particularly, feedstock flexibility empowered by reliable inventories of biomass and waste streams (e.g., industrial, construction and demolition, electronic wastes) may contribute to reduced risks.

Reduce processing-associated risks. Improved understanding of material properties (e.g., particle size distributions) and chemical properties (e.g., solubility) would reduce risks in developing upcycling, downcycling, or recycling technologies. Furthermore, developing broadly applicable feedstock processing technology will open doors to lower-risk bioprocesses. Particularly in distributed systems, process intensification in the circular economy is not sufficiently explored for its potential to reduce cost, energy consumption, and emissions. Greater insight into challenges from scaling up decentralized waste conversion processes and their solutions would reduce risks on the path to commercialization.

Engage stakeholders to reduce risk. Early stakeholder engagement throughout the value chain is essential. Important stakeholders include agricultural groups that work with farmers and community groups that influence local approaches to recycling. Stakeholders should be engaged to set property or composition targets for waste-derived materials and to help set common targets that reduce companies' risks in selecting viable applications.



Source: Closed Loop Partners (2021)

Lawrence Berkeley National Laboratory > Jay D. Keasling, Senior Faculty Scientist, Lawrence Berkeley National Laboratory

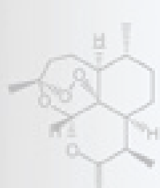
Background

Synthetic biology is the design and construction of biological systems to solve important problems or to better understand a biological phenomenon. Developments in synthetic biology support the biomanufacturing and commercialization of biomanufacturing technologies. The Keasling Lab focuses on the development of basic synthetic biology tools to make it easier to design, construct, and control metabolism inside cells. The lab engineers microbes to turn sugar and other feedstocks into high-value chemicals that are sustainable, stimulate economic development, and create jobs. New companies, such as Amyris, Inc. and Demetrix, Inc., were founded to develop, optimize, and scale up these technologies.

Several lab-developed products have been commercialized using engineered microorganisms based on research from Keasling Lab:

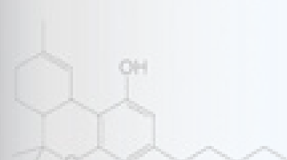
Artemisinin, a fast-acting, effective anti-malaria drug.

- **Challenge:** Typical production from wormwood plant makes production expensive for large-scale use.
- **Synthetic biology solution:** Engineered yeast produces artemisinic acid, which is converted into artemisinin. Microbial production of artemisinic acid reduces cost and stabilizes supply.
- **Commercialization:** Process was patented by UC Berkeley and then given to Amyris, Inc. and Sanofi for scale, leveraging royalty-free, exclusive licenses for the developed world. About 51 million treatments have been delivered to Africa. Bulgaria-based Heuvepharma poised to produce 100 to 150 million treatments annually, roughly one-half of the world's need.



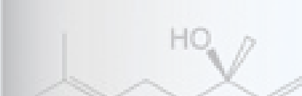
Cannabinoids for medical, pharmaceutical, cosmetic, and recreational use.

- **Challenge:** Typical production from farmed or greenhouse sources limits large-scale use.
- **Synthetic biology solution:** Engineered yeast produces a biosynthetic pathway for cannabinoids and dedicated enzymes from cannabis, enabling microbial production.
- **Commercialization:** Licensed to Demetrix, Inc., for scale-up.



Hops, the key to flavor in hoppy beers.

- **Challenge:** Typical agricultural production limits large-scale use.
- **Synthetic biology solution:** Engineered yeast produces and optimizes linalool and geraniol, the primary flavor determinants in hops.
- **Commercialization:** UC Davis scaled the technology and launched Berkley Yeast, an engineering yeast with a range of flavor components for beer and wine. Breweries like the consistent flavor and reduction in production time.



Concluding Group Discussion

At the end of Day 2, participants re-convened to evaluate the key takeaways from the breakout groups. The results from both days of the workshop were synthesized into overall conclusions and next steps.

Overall Takeaways

- Scaling the circular bioeconomy requires close integration with industrial partners, careful consideration of complexity, and a systems-level approach.
- Research needs range from improving our fundamental knowledge of non-ideal biological systems to improving models that capture the interconnections among the systems that constitute the circular economy.
- There is a need to consider global approaches in waste reduction through international collaboration.
- Post-consumer waste streams must be reduced through recycling and composting.
- Hybrid chemical-biological systems for creating new, recyclable bio-based materials and for recycling waste hold promise and merit development.
- The overall notion of the bioeconomy is becoming more attractive. Human behavior as well as inconsistent policy remain major barriers to its success.
- Sharing fundamental, pre-competitive intellectual property is critical to support development and application of the technologies needed to enable the circular bioeconomy.
- Systems of support to scale high-impact research require focus and investment.
- Research funding models must be evaluated and potentially redesigned in the context of the circular bioeconomy, which is highly interdisciplinary and holds unique challenges.
- Funding and investment systems that provide incentives for innovation and collaboration must be developed.
- Value chains across the stakeholder continuum should be designed to reduce risk.

Next Steps

- The circular economy has over 100 definitions.[10] Arriving at a consensus definition with strong stakeholder buy-in will clarify objectives and paths to action; this could be accomplished through a targeted workshop. With more agreement on a definition, methods to quantify circularity and overall sustainability through modeling frameworks – including life cycle assessment – may then be addressed through a second workshop. This would enable the modeling community to work more closely with the technology development community to design circular, sustainable, biologically-based systems.
- Major waste streams should be quantified and characterized at the regional level to the best fidelity possible. This should include industrial wastes that potentially hold high value. This inventory will illuminate efforts to find regional approaches to the circular bioeconomy.
- New models for collaboration should be explored to catalyze collaboration among the diverse stakeholders.
- The concept for pre-competitive data sharing was raised numerous times. A framework should be prepared and shared for comment within the stakeholder community.

Appendix A: The Research Landscape for a World without Waste

Elsevier research analysts Bamini Jayabalasingham and Daniel Calto presented the results of a review of the global circular bioeconomy R&D landscape.[11] Bibliometric analyses were based on peer-reviewed publications (articles, reviews, and conference papers) and focused on the period 2001-2020. The source for all bibliometric data was the Scopus database. Scopus includes data and linkages across 83 million items from 80 thousand affiliations and 17 million authors. It is the largest curated abstract and citation database of peer-reviewed literature and provides a comprehensive view on the research landscape.

Results

Over the past 20 years, global research on the workshop topic has been growing at a rapid pace (Figure 1). This was particularly true for the last five years; nearly one-third of the 312,402 circular bioeconomy publications over the last 20 years was published between 2018 and 2020, and the research area is growing much more rapidly than the whole corpus of research literature. The compound annual growth rate of circular bioeconomy publications was 11.4% over the years 2001-2020, compared to the compound annual growth rate of all publications at 5.6%. The compound annual growth rate of circular bioeconomy publications over recent years (2017-2020) was even greater at 15.5%.

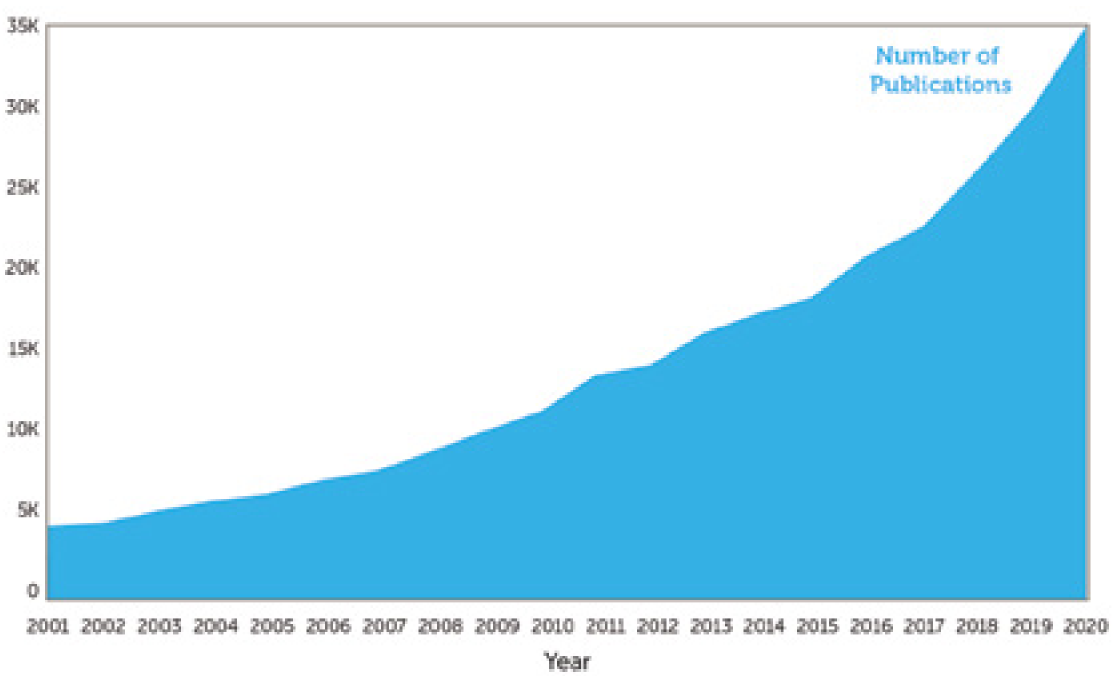


Figure 1 | Number of publications on a circular bioeconomy, 2001-2020.Source: Scopus

This growth in circular bioeconomy publication output has been driven by continued focus on the research area from the United States and European countries, as well as a rapid increase in publications from China and India (Figure 2). These data show that China published the most circular bioeconomy research, with 62,115 publications during the period 2001-2020, with particularly high growth over the last four years of the period (2016-2020). The United States and India followed with 49,771 and 24,166 publications during the period, respectively. Several of the current European Union member states (EU 27) were also among the top countries publishing on circular bioeconomy and together, EU 27 publications surpassed the United States and China in terms of publication output with 94,000 publications. However, despite this high output by both the United States and China, other countries such as India, Brazil, and Spain dedicated more of their overall research efforts in this area. Circular bioeconomy publications by these countries represented 1.2-1.3% of their national research output. In contrast, 0.5% of total U.S. research output related to circular bioeconomy. Publication output trends among top countries and jurisdictions publishing research in this area shows that it is of interest to both established and emerging research countries and jurisdictions, but it looks to be especially important for developing economies and middle-income countries.

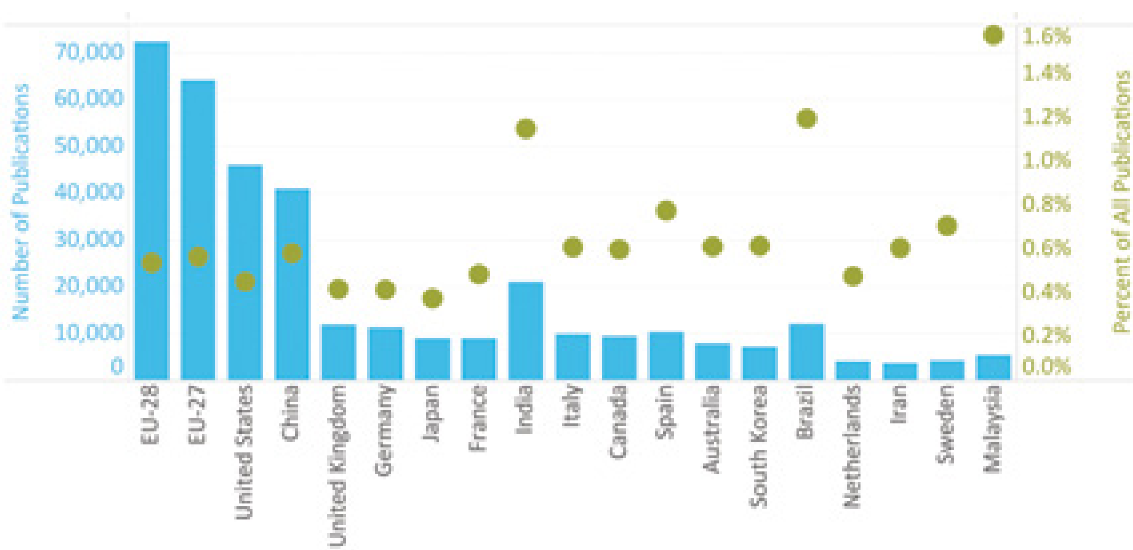


Figure 2 | Number of circular bioeconomy research publications and percent of the regional research portfolio represented by circular bioeconomy research, 2001-2020. Source: Scopus

When examining the research over the last five years of the period (2016 – 2020), China's output was nearly double that of the United States and had an average field-weighted citation impact[12] that is comparable to that of the United States (Table 1). Both the United States and European countries continued to play an important role and produce numerous highly cited papers, as shown by the number of papers among the top 10% most cited. It is notable, however, that this area of research has been a major focus not only for China but also for India, Brazil, and other rising research economies. India, with 3,494 publications, produced nearly as many papers as the United States in 2020.

		Publications				
	Country/Region	Total	Among Top 10% Most Cited	Cited in USPTO Patents	Cited in WIPO Patents	Average Field-weighted Citation Impact
1	China	35,269	12,974	99	204	1.5
2	United States	18,568	5,957	186	205	1.5
3	India	12,577	3,434	21	49	1.3
4	Spain	6,940	2,537	19	61	1.6
5	Brazil	6,891	1,565	7	33	1.1
6	Italy	6,792	2,381	22	51	1.7
7	United Kingdom	6,594	2,599	18	78	2.0
8	Germany	6,239	2,033	24	92	1.6
9	Australia	5,066	2,236	10	38	1.9
10	Canada	4,962	1,602	24	47	1.5
11	Malaysia	4,641	1,209	11	19	1.4
12	France	4,366	1,357	19	59	1.6
13	South Korea	4,353	1,594	29	47	1.6

Table 1 | Number of CB research publications from each region and percent of the research portfolio represented by circular bioeconomy research, 2016–2020.

In addition to the heavily international scope of circular bioeconomy research, the span of circular bioeconomy research topics exhibits a wide spectrum of fields. Turning to U.S. output specifically, it is notable that a variety of major research fields are represented. Approximately one-quarter of circular bioeconomy output is in the environmental sciences. Disciplines related to energy, chemical engineering, agriculture and biological sciences, general chemistry, and general engineering each represent around 7-11% of all publications examining the circular bioeconomy.

When we look at top funders for circular bioeconomy research in the United States, the National Science Foundation is the leading funding sponsor by a wide margin, funding nearly 3,000 projects between 2016 and 2020 (Table 2). The Department of Energy is both the second-largest research funder and one of the most important contributors to the circular bioeconomy literature, especially through contributions made by its National Renewable Energy

Laboratory and Oak Ridge National Laboratory (Table 3). The US Department of Agriculture, the National Institutes of Health, and the Environmental Protection Agency also fund significant numbers of circular bioeconomy research proposals.

Funding Sponsor	Number of Publications
National Science Foundation	2,992
U.S. Department of Energy	1,782
U.S. Department of Agriculture	1,049
National Institute of Food and Agriculture	817
Office of Science	741
National Institutes of Health	488
Office of Energy Efficiency and Renewable Energy	435
National Nuclear Security Administration	412
Laboratory Directed Research and Development	411
U.S. Department of Health and Human Services	395
U.S. Environmental Protection Agency	356
Biological and Environmental Research	270
U.S. Department of Defense	253
Bioenergy Technologies Office	235
National Renewable Energy Laboratory	166
National Institute of General Medical Sciences	164
Oak Ridge National Laboratory	163
Basic Energy Sciences	142
National Institute of Environmental Health Sciences	138
National Oceanic and Atmospheric Administration	132
National Aeronautics and Space Administration	125

Table 2 | Leading U.S. funders of U.S circular bioeconomy research, 2016–2020. Source: Scopus

In most research areas, universities make the largest contributions to the literature by a wide margin. However, that is not the case for circular bioeconomy research. U.S. federal government agencies, especially the Department of Agriculture and various Department of Energy laboratories, are themselves among the largest contributors to the research (Table 3).

The Department of Agriculture has contributed the most to the literature in this area over the last 20 years, and the Department of Energy has emerged as a major contributor over the last 10.

		Publications				
Institution	Sector	Total	Among Top 10% Most Cited	Cited in USPTO Patents	Cited in WIPO Patents	Average Field-weighted Citation Impact
United States Department of Agriculture	Government	887	203	11	4	1.27
United States Department of Energy	Government	600	236	28	20	1.70
University of Minnesota Twin Cities	Academic	452	194	10	6	1.78
Oak Ridge National Laboratory	Government	442	166	8	4	1.51
University of Wisconsin-Madison	Academic	421	154	13	9	1.74
University of Florida	Academic	415	140	3	0	1.74
Pennsylvania State University	Academic	338	122	3	1	1.53
University of California at Berkeley	Academic	326	137	4	13	2.04
Cornell University	Academic	312	137	6	9	2.09
Ohio State University	Academic	289	111	1	4	1.70
Lawrence Berkeley National Laboratory	Government	281	118	10	10	1.87
Pacific Northwest National Laboratory	Government	241	98	4	6	1.75
University of Michigan, Ann Arbor	Academic	240	98	2	1	1.85
Massachusetts Institute of Technology	Academic	237	112	5	9	1.95
University of Washington	Academic	228	77	3	3	1.84

Table 3 | Top US institutions publishing circular bioeconomy research and aggregate statistics on their publication output (number of publications) and citations, 2016–2020. Source: Scopus

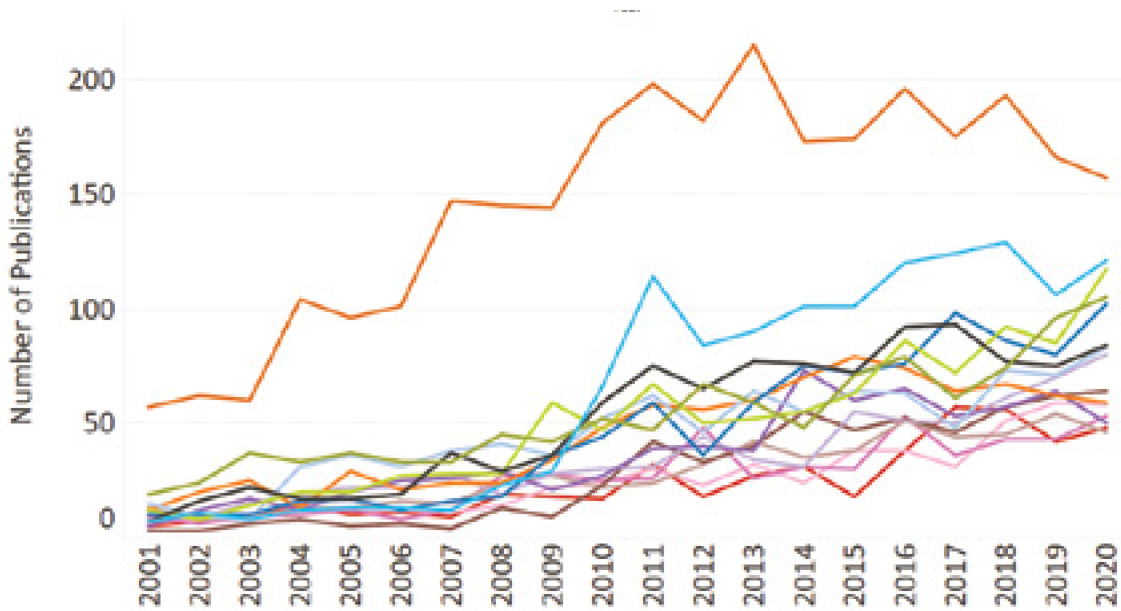


Figure 3 | Trends in the number of circular bioeconomy research publications by US institution, 2001–2020. Source: Scopus

So how can we more distinctly define the range of circular bioeconomy research in the United States and globally? One method is topic modelling global research using recent technological capabilities. By using machine learning techniques, semantic and NLP processing, and multiple structured thesauri and ontologies covering all fields of research, we can use a direct citation method to parse the entire global corpus of literature, as represented by Scopus, into around 100,000 specific research topics. Each of the roughly 83 million papers in Scopus is machine-read and assigned to a single topic via a direct citation analysis, which matches cited-cited by pairs for network centrality and semantic similarity. This method is especially well-suited to the characterization of multidisciplinary research, as it does not proceed from any preexisting top-down categorization of research fields but determines the topics using a bottom-up analysis. Thus, if a paper is published in the journal of biochemistry, but 20% of its citations are to biotechnology journals, and 15% of its citations relate to computer science topics, these multidisciplinary references are fully ingested by the model.

In addition, all topics are assigned a topic prominence score, which is calculated looking at previous citations to the papers in the topic (about 50% of score), the current usage and downloads of records in Scopus (about 40%), and the journal's CiteScore metric (about 10%). The prominence score can be broadly described as an analogue for the current momentum of the topic, including the level of funding and underlying publication trends over time.[13,14]

Topic	U.S. Publications			Prominence Percentile
	Scholarly Output	Share of Relevant Publications in Topic	Field-weighted Citation Impact	
Saccharification; Delignification; Ethanol Production	432	9.5%	1.32	99.89
Microplastics; Marine Debris; Litter	319	5.8%	5.02	99.99
Bio-Oil; Pyrolysis Oils; Guaiacol	314	7.4%	1.87	99.94
Biochar; Soil Amendments; Black Carbon	291	3.9%	2.47	99.97
Photobioreactors; Nutrient Removal; Scenedesmus	263	10.6%	1.44	99.77
PPCP; Micropollutant; Carbamazepine	242	4.9%	1.85	99.96
Photobioreactors; Nannochloropsis; Chlorella Sorokiniana	228	5.1%	1.27	99.89
Anaerobic Digestion; Digester; Methane Production	225	4.7%	1.10	99.91

Table 4 | Topics of Prominence represented in circular bioeconomy literature, 2016–2020.

Closely related topics can be further aggregated into topic clusters to provide a different perspective on the research. The most highly represented cluster in circular bioeconomy research is microbial fuel cells, anaerobic digestion, and bioreactors. Delving further into this topic cluster, we can discover more fine-grained detail about this specific area of research. This cluster is a rapidly growing area of research, with an average year-over-year growth of 8% over the period 2016–2020. The U.S. Department of Agriculture also makes significant contributions to the research literature in this cluster.

Companies also published many papers in this research area, primarily in collaboration with universities. Further analysis can elucidate the specific relationships between individual universities and companies doing joint research in the area and track the global patenting activity that is citing the research on microbial fuel cells, anaerobic digestion, and bioreactors being done over the past two decades.

Given the importance of catalyzing not only relevant research, but also innovating real-world solutions that can help make the circular bioeconomy a reality, a network analysis shows how the top 20 U.S. organizations in each sector (academic, government, and corporate) collaborate in publishing circular bioeconomy research (Figure 4). This analysis shows that the U.S. Department of Agriculture and the U.S. Department of Energy are central to the network. The U.S. Department of Agriculture is connected to several academic institutions, with the strongest connections to the University of Wisconsin-Madison and the U.S. Department of

Energy. The U.S. Department of Energy is connected to many other governmental institutions and fewer academic institutions compared to the U.S. Department of Agriculture. The University of Wisconsin-Madison is strongly connected to both the U.S. Department of Agriculture and the U.S. Department of Energy. Other institutions of interest in the network are the University of Minnesota Twin Cities, which is connected to many institutions in the network, making it very central to the network, and the University of California at Berkeley, which is strongly connected to the U.S. Department of Energy and the Lawrence Berkeley National Laboratory. **Of note, no corporate institutions were tied to the network map, indicating that none of these institutions were connected to three or more institutions in the network by at least two collaborative publications.**

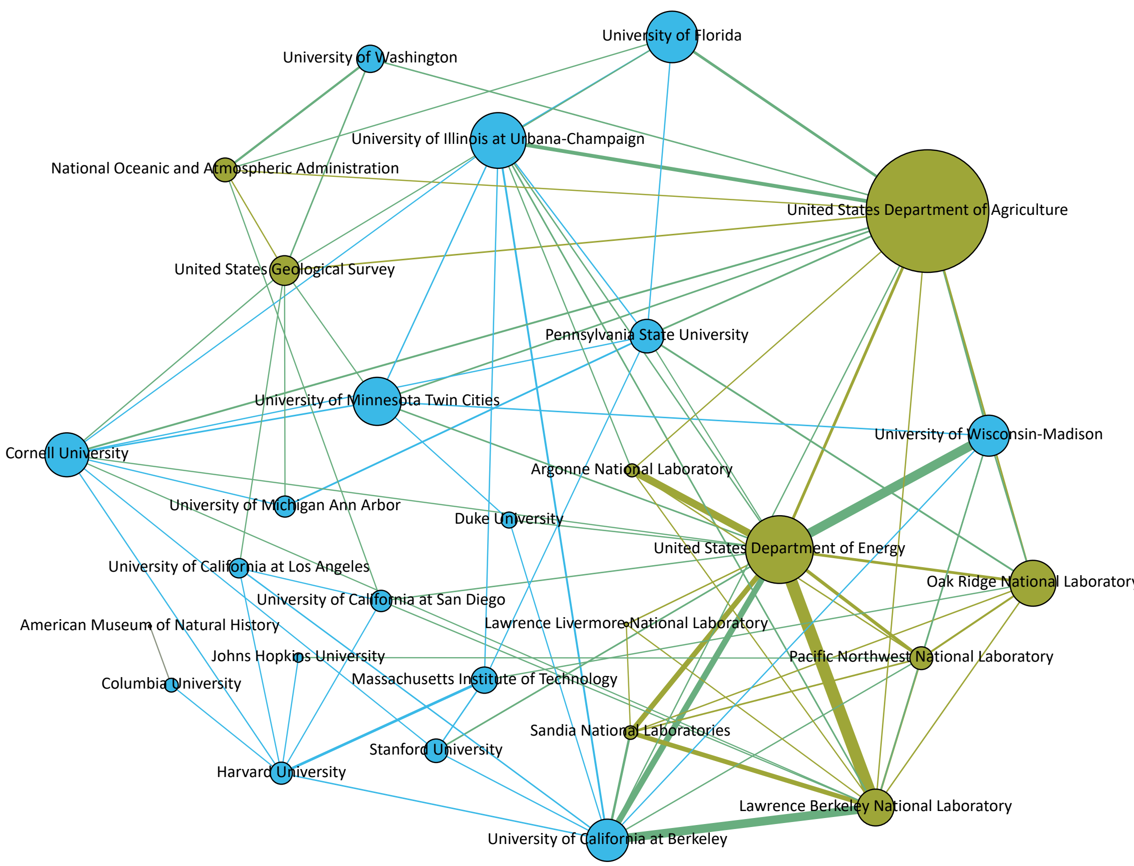


Figure 4 | Network collaboration map based on the 20 U.S institutions in each of the academic (pink) and government (blue) sectors that have published the most circular bioeconomy research from 2016-2020. Map is limited to institutions that have published at least two publications in collaboration with at least two other institutions. Circle size is indicative of institutional circular bioeconomy publication output during the period 2016-2020 and the thickness of connecting lines is indicative of the number of collaborative publications published by the connected institutions.

In closing, the view described of the research landscape in this area is one that is provisional and not definitive. The definition of circular bioeconomy research, and thus the papers included in analyses, were determined by the creation and application of multi-factor, multi-term queries developed in collaboration with subject matter experts in the domain. Research areas – particularly multidisciplinary ones such as circular bioeconomy – have fuzzy edges and may be defined more narrowly or more broadly by individual scholars or groups of experts. This is an inherent structural factor in the model itself. Nonetheless, we believe that the set of papers gathered by the query are a good representation of the research area overall and capture both fine-grained details of very specific research questions and paradigms and a broader overview of the research area as a whole.

Conclusions from the Research Landscape

Research focused on the goal of a world without waste through a circular bioeconomy has grown internationally at a rapid pace. Between 2001 and 2020, over 300,000 research papers were published that focus on this goal. During this time, the global research output in this topic area grew at a compound annual growth rate of 11.4%, outpacing the compound annual growth rate of overall global research output by almost six percentage points. While the United States and China published the most research on a circular bioeconomy, several of the top countries publishing in this area dedicated a higher percentage of their research portfolio to the topic, including India, Brazil, and Spain (1.2-1.3% of each country's research portfolio), indicating the high priority status of this research topic in those countries. Looking at both the 20-year period and especially the last five years, research in a circular bioeconomy appears to be especially important in developing economies and middle-income countries. India is quickly catching up to the United States in terms of annual publication output.

Research in this area spans a wide spectrum of fields, including environmental science, energy, chemical engineering, and agriculture and biological sciences. In the United States, the research also spans the sectors, with federal government institutions contributing the most research. The Department of Agriculture has contributed the most to U.S. circular bioeconomy literature over the last 20 years, and the Department of Energy has emerged as a major contributor over the last decade.

In the United States, clusters of research topics, such as microbial fuel cells, anaerobic digestion, and bioreactors, are highly represented within the corpus of research on a circular bioeconomy. Research on this cluster had an average year-over-year growth of 8% between 2016 and 2020. Additionally, research in these topic clusters was published by a diverse group of researchers, including a substantial number of contributions from corporate institutions (in collaboration with academic institutions). Together, these findings show the diversity of players, disciplines, and topics in research on a World Without Waste through a circular bioeconomy.

Appendix B:
World without Waste Workshop Agenda

Thursday, August 19, 2021

11–11:10 a.m.	**Workshop Introduction** Christina Payne, National Science Foundation Anthony Boccanfuso, UIDP
11:10–11:30 a.m.	**Opening General Framing Session** Ken Barrett, BASF Jennifer Dunn, Northwestern University Chris Hewitt, BASF Mike McMahon, Northwestern University Charge to participants, workshop rules, and goals. Organizers will introduce the main theme of Day 1, which is how we can integrate the four key themes.
11:30 a.m.–12:30 p.m.	**Review of the Current R&D Landscape** Bamini Jayabalasingham, Elsevier Elsevier will provide findings from their review of the nation's current sustainable agriculture capabilities and benchmark against global activities.
1–2:30 p.m.	**Concurrent Breakout Sessions:** **Key Workshop Themes** Participants will be assigned to groups prior to workshop. Groups will be interdisciplinary and from different industries. Each group will determine the state-of-the-art methods in each field, discuss limitations/gaps, and determine how to integrate biological and computational methods toward desired outcomes.
1–2:30 p.m.	**Biological Systems Design** Yannick Bomble, National Renewable Energy Laboratory Taraka Dale, Los Alamos National Laboratory Discussion on expanding knowledge of natural biological systems across all scales of life and understanding how to leverage such knowledge in design. Discussion will include gaps in understanding of biotechnology innovation, synthetic biology tools, and biodiversity and environmental science.
1–2:30 p.m.	**Sustainable Biosourced Materials and Products** Margaret MacDonell, Argonne National Labs Anne Shim, BASF Discussion on the economically competitive and sustainable biosourced materials and how to process them in environmentally benign ways; product creation with end-of-life properties that enable reuse or recycling; practical adoption of biosourced materials and products; and design of materials that actively contribute to the foundation of a circular bioeconomy.

Thursday, August 19, 2021

1–2:30 p.m.	**Biomanufacturing** Chloe Liang, Northwestern University Brent Shanks, Iowa State University Discussion on novel manufacturing infrastructure processes, distributed manufacturing models, process intensification, and real-time characterization and control methods.
1–2:30 p.m.	**Enabling Circularity** Leslie Fran, Dow Chemical Company Kat Knauer, Novoloop Discussion on data and computing infrastructure, thoughtful consideration of societal, environmental, and economic factors, and strong community engagement and workforce development.
3–4:15 p.m.	**Breakout Session Report Outs**
4:15–5 p.m.	**Concluding Session/Identification of Key Takeaways** Concluding Session/Identification of Key Takeaways Ken Barrett, BASF Jennifer Dunn, Northwestern University Chris Hewitt, BASF Mike McMahon, Northwestern University Come together as a group to summarize answers from each of the breakout topics and identify key takeaways from Day 1.

Friday, August 20, 2021

11–11:30 a.m.	**Welcome and Day 1 Recap** Ken Barrett, BASF Jennifer Dunn, Northwestern University Chris Hewitt, BASF Mike McMahon, Northwestern University
11:30 a.m.–12:30 p.m.	**Translational Case Study** Hannah Friedman, Closed Loop Partners Jay Keasling, UC Berkeley
1–2:30 p.m.	**Concurrent Breakout Sessions: Translating Basic and Use-Inspired Research**
1–2:30 p.m.	**Regional and International Approaches** Chris Hewitt, BASF Kathleen Liang, North Carolina A&T University Regions (domestically and internationally) differ in their variety of bio-based feedstocks, industrial makeup, supply chains, and markets. Consideration in leveraging this uniqueness towards innovation in different regions that pushes the circular bioeconomy towards near-term impact. Evaluating and learning from current stakeholders and the experiences of other nations while striving to build and maintain national prominence in the elements and implementation of the circular bioeconomy.
1–2:30 p.m.	**Innovation Recipes and Collaboration** Linda Molnar, NSF Stuart Rowan, University of Chicago Considerations for design strategies which include fundamental science, use-inspired research, and high-risk research that will result a continuous cycle of scientific advances that accelerate the circular bioeconomy. Leveraging the unique abilities of circular bioeconomy stakeholders towards its realization. Discussing the optimal role for each of the stakeholders including academia, industry, start- up organizations, foundations, NGOs, and government agencies.
1–2:30 p.m.	**Public Engagement** Gayle Bentley, Department of Energy Michelle Wander, University of Illinois Public engagement and acceptance are critical to moving from a linear, fossil fuel-based economy to one built on circular approaches that leverage renewable resources. Building of public interest in and support of the circular bioeconomy.

Friday, August 20, 2021

1–2:30 p.m.	**Reducing Risk** Alan Allgeier, University of Kansas Michael Köepke, LanzaTech Evaluating technologies that are ready to advance to market in the near term (less than 5 years) and longer term (decadal) and reviewing the community of stakeholders involved in the reduction of risks and barriers towards realization of technology commercialization. Identifying critical barriers to near term adoption and implementation of technologies to enable the circular bioeconomy and how stakeholders can contribute to and benefit from overcoming those barriers.
3–4:15 p.m.	**Report Outs and Discussion**
4:15–5 p.m.	**Concluding Group Discussion** Ken Barrett, BASF Jennifer Dunn, Northwestern University Chris Hewitt, BASF Mike McMahon, Northwestern University Come together as a group to summarize answers from each of the breakout topics and identify key takeaways from Day 2.

Appendix C: Participant List

Alireza Abbaspourrad, Cornell University

Christian Adams, International Flavors & Fragrances

Farhan Ahmad, Invista

Haleema Alamri, Aramco

Greg Aldrich, Kansas State University

Alan Allgeier, University of Kansas

Ana Andzic Tomlinson, University of New Mexico

Bhavik Bakshi, The Ohio State University

Miki Banu, University of Michigan, Ann Arbor

Katie Barry, International Ingredient Corporation

Ezra Bar-Ziv, Michigan Technological University

Jacob Beal, Raytheon Technologies

Mary Biddy, Ineos Aromatics

Melissa Bilec, University of Pittsburgh

Ameerah Bokhari, Aramco

Lauren Burgos, Closed Loop Partners

Michael Burkart, UC San Diego

Daniel Calto, Elsevier

Younas Dadmohammadi, Cornell University

John Dorgan, Michigan State University

John Dorgan, Michigan State University

Jennifer Dunn, Northwestern University

James Eagan, University of Akron

Leslie Fan, Dow Chemical Company

Michail Fragkias, Boise State University

Doug Friedman, BioMADE

Ann Gabriel, Elsevier

Demetria Giannisis, Northwestern University

Wendy Goodson, Ginkgo Bioworks, Inc.

Eleanor Hadley Kershaw, University of Nottingham

Jeanne Hankett, BASF

Jeanette Hanna, BASF

David Hanson, University of New Mexico

Bryan Haynes, Kimberly-Clark Corporation

Christopher Hewitt, BASF

Victoria Holden, Full Circle Microbes, Inc

Bamini Jayabalasingham, Elsevier

Kelsey Jensen, Aspire Food Group

Michael Jewett, Northwestern University

Colleen Josephson, VMware

Anne-Marie Kaluz, Closed Loop Partners

Michael Koepke, , LanzaTech

Raj Krishnaswamy, Braskem

Dagmar Kunsmann-Keitel, BASF

Julius Kusuma, Facebook

Nastassja Lewinski, Virginia Commonwealth University

Kathleen Liang, North Carolina A&T University

Jennifer Louie, Closed Loop Partners

Ting Lu, University of Illinois Urbana-Champaign

Benedetto Marelli, Massachusetts Institute of Technology

Stephen Mayfield, UC San Diego

Karen McDonald, UC Davis

James McLellan, Queen's University

Mike McMahon, Northwestern University

Gnanambal Naidoo, Langston University

Nitin Nitin, University of California, Davis

Jeff Nivala, University of Washington

Justin Notestein, Northwestern University

Kimberly Ogden, University of Arizona

Elsa Olivetti, Massachusetts Institute of Technology

M. Soledad Peresin, Auburn University

Kristala Prather, Massachusetts Institute of Technology

Itzel Ramos-Solis, bp

Sridhar Ranganathan, Kimberly-Clark Corporation

Alicyn Rhoades, Penn State University

Stuart Rowan, University of Chicago

Kostas Sakkalis, bp

Kirsty Salmon, bp

Brian Schmatz, BASF

Jill Seebergh, The Boeing Company

Brent Shanks, Iowa State University

Anne Shim, BASF

Gang Si, Procter & Gamble

Volker Sick, University of Michigan

Shweta Singh, Purdue University

Sameer Talsania, PepsiCo, Inc.

Phil Taylor, Bayer

Stephanie Tofighi, New Mexico Bioscience Authority

John Torkelson, Northwestern University

Kenji Ueda, SONY

Phillip Vinson, Procter & Gamble

Maggie Waldron, Northwestern University

Michelle Wander, University of Illinois

Gale Wichmann, Amyris

Xiong Yu, Case Western Reserve University

Cathy Zhang, Saint-Gobain

Fuzhong Zhang, Washington University, St. Louis

Fu Zhao, Purdue University

Appendix D: Workshop Observers

Mitra Basu, National Science Foundation

Kathryn Beers, NIST

David Berkowitz, National Science Foundation

Yannick Bomble, National Renewable Energy Laboratory

Robin Brigmon, Savannah River National Laboratory

Alberta Carpenter, National Renewable Energy Laboratory

Adrienne Cheng, National Science Foundation

Karen Con, National Science Foundation

Taraka Dale, Los Alamos National Lab

Max Delferro, Argonne National Laboratory

Steve DiFazio, National Science Foundation

Victoria Finkenstadt, USDA

Bianca Garner, National Science Foundation

J Aura Gimm, Department of Defense

Theresa Good, National Science Foundation

Bruce Hamilton, National Science Foundation

Maureen Kearney, National Science Foundation

Katrina Knauer, National Renewable Energy Laboratory

Brady Lee, Savannah River National Laboratory

Sheng Lin-Gibson, NIST

Andrew Lovinger, National Science Foundation

Margaret MacDonell, Argonne National Laboratory

Mary Maxon, Lawrence Berkeley National Laboratory

Gail McLean, Department of Energy

Linda Molnar, National Science Foundation

Cristina Negri, Argonne National Laboratory

Christina Payne, National Science Foundation

Steven Peretti, National Science Foundation

Shafiqur Rahman, USDA-NIFA

Lynn Rothschild, NASA

Steve Smith, National Science Foundation

Elizabeth Strychalski, NIST

Anne Sylvester, National Science Foundation

Appendix E: Pre-Event Survey

We look forward to your participation at the upcoming "World Without Waste" workshop. Our goal is to convene stakeholders from multiple sectors and disciplines to design a future circular bioeconomy that is innovative, economical, and sustainable. We will focus on four theme areas:

1. Biological Systems Design,
2. Sustainable Biosourced Materials and Products,
3. Biomanufacturing, and
4. Enabling Circularity.

So our exploration of each of those theme areas is efficient and productive, we ask that you give us your feedback on the following. We also welcome your written comments below.

Please help us set the stage for the workshop by completing the survey below. Please respond by August 12, 2021.

For each theme below, please rate the importance of the topics for industry and academia to collaboratively expand knowledge in and remove barriers to achieving a circular bioeconomy.

Biological Systems Design

	Not Important	Slightly Important	Moderately Important	Important	Very Important
Evolutionary biological processes	◯	◯	◯	◯	◯
Basic cellular principles	◯	◯	◯	◯	◯
Microbial community behaviors in processes that convert wastes and/or biomass to desired products	◯	◯	◯	◯	◯
Microbial biodiversity	◯	◯	◯	◯	◯

Sustainable Biosourced Materials and Products

	Not Important	Slightly Important	Moderately Important	Important	Very Important
Cost competitiveness to fossil derived equivalents	◯	◯	◯	◯	◯
Displacement effects of bioresoureced material	◯	◯	◯	◯	◯
Feedstock (biomass, wastes) supply chain development	◯	◯	◯	◯	◯
Feedstock flexible processes	◯	◯	◯	◯	◯
Feedstock preprocessing techniques	◯	◯	◯	◯	◯
Importance of biosourced products themselves being recyclable (may be addressed already under the “enabling circularity heading)	◯	◯	◯	◯	◯
Platform technologies addressing primary materials for fossil derived plastics	◯	◯	◯	◯	◯
Social implications of bioresources materials supply chains	◯	◯	◯	◯	◯
Sustainable agriculture	◯	◯	◯	◯	◯
Volume alignment between source and market volumes to enable 100% replacement of incumbent material	◯	◯	◯	◯	◯

Biomanufacturing

	Not Important	Slightly Important	Moderately Important	Important	Very Important
Development of new manufacturing paradigms that leverage waste and biomass feedstocks	◯	◯	◯	◯	◯
Development of robust conversion processes for different feedstock types (including process efficiency)	◯	◯	◯	◯	◯
Addressing challenges in translation such as process efficiency, understanding and mitigating impact of raw material differences, reducing cost, creating transparency in assessing carbon impact	◯	◯	◯	◯	◯

Enabling Circularity

	Not Important	Slightly Important	Moderately Important	Important	Very Important
Insights into how a circular bioeconomy might vary regionally	○	○	○	○	○
Design of materials that are inherently recyclable and degradable to benign products	○	○	○	○	○
Development of common data storage and sharing protocols and platforms	○	○	○	○	○
Analytical frameworks for evaluation of biosourced materials and product sustainability	○	○	○	○	○
Effects of a circular bioeconomy on disadvantaged groups	○	○	○	○	○
Training of scientists and engineers in the concepts and technology of the circular bioeconomy	○	○	○	○	○

Please offer any additional relevant topics or additional comments you'd like to share.

Notes

References

[1] *The New Plastics Economy, Ellen McArthur Foundation 2017*

[2] *World Economic Forum, Ellen MacArthur Foundation, McKinsey & Company, A new plastics economy: rethinking the future of plastics (2016). ellenmacarthurfoundation.org/publications.*

[3] *Forti, Vanessa, Balde, Cornelis P., Kuehr, Ruediger and Bel, Garam, The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential, (Bonn, Geneva and Rotterdam: United Nations University/United Nations Institute for Training and Research, International Telecommunication Union, and International Solid Waste Association, 2020).*

[4] *United States Environmental Protection Agency. Advancing Sustainable Materials Management: 2018 Fact Sheet (2020). https://www.epa.gov/sites/default/files/2021-01/documents/2018_ff_fact_sheet_dec_2020_fnl_508.pdf.*

[5] *Bibliometric analyses were based on peer-reviewed publications (articles, reviews, and conference papers) and focused on the period 2001-2020. The source for all bibliometric data was the Scopus database. Scopus includes data and linkages across 83 million items from 80 thousand affiliations and 17 million authors. It is the largest curated abstract and citation database of peer-reviewed literature and provides a comprehensive view on the research landscape. See Appendix 1 for an expanded review of the research landscape. The full research report is available at uidp.org.*

[6] *See https://www.closedlooppartners.com.*

[7] *https://bigdatahubs.org/about-the-big-data-innovation-hubs/*

[8] *https://www.gov.uk/guidance/case-programme*

[9] *http://parts.igem.org*

[10] *Kircherr, J., Reike, D., Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions.* Resources, Conservation, and Recycling*. 2017, 127: 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005*

[11] *See Appendix 1 for an expanded review of the research landscape. The full research report is available at uidp.org.*

[12] *Field-Weighted Citation Impact (FWCI) is an indicator of the citation impact of a publication. It is calculated by comparing the number of citations received by a publication with the number of citations expected for a publication of the same document type, publication year, and subject. An FWCI of more than 1.00 indicates that the entity's publications have been cited more than would be expected based on the global average for similar publications; for example, a score of 2.11 means the entity's publications have been cited 111% more than the world average. An FWCI of less than 1.00 indicates that the entity's publications have been cited less than would be expected based on the global average for similar publications; for example, an FWCI score of 0.87 means the publications have been cited 13% less than the world average.*

[13] *Klavans, R. and Boyack, K. W. (2017). Which Type of Citation Analysis Generates the Most Accurate Taxonomy of Scientific and Technical Knowledge?.* Journal of the Association for Information Science and Technology*, 68: 984–998. https://doi.org/10.1002/asi.23734*

[14] *Klavans, R., and Boyack, K. W. (2017). Research Portfolio Analysis and Topics of Prominence. Journal of Informetrics, 11(4): 1158-1174, 2017 https://doi.org/10.1016/j.joi.2017.10.002*

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