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Feedstocks of the Future for a Circular U.S. Bioeconomy

A SUMMARY FROM A STAKEHOLDER CONVENING

JUNE 2023

Suggested Citation

RedCorn, R., Croft, G., McGill, R., Reich, J. 2023. Feedstocks of the Future for a Circular U.S. Bioeconomy: A Summary from a Stakeholder Convening. Washington, DC: FFAR-Schmidt Futures.

This publication is available to the public in PDF format at FFAR.org

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Acknowledgements

The Foundation for Food & Agriculture Research (FFAR), in partnership with Schmidt Futures, organized this report and the convening it covers. A team including a diverse Steering Committee of experts, the organizers, a scientific writer, a professional facilitator, note-takers and participants collaborated in a process that resulted in this report. The conveners thank and recognize the following for their contributions:

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Key Definitions

Bioeconomy – Economic activity that is driven by research and innovation in the life sciences and biotechnology. It is enabled by technological advances in engineering, computing, and information sciences.

- **Circular bioeconomy** – An economy that forgoes the traditional linear economic model of "take-make-consume-throw away" to create a system in which waste products serve as inputs to create highly valued products and materials, that are used as long as possible, and reused without drawing down limited resources or generating wastes that are disposed into the environment. The circular economy is enabled by advances in biotechnology, modeling, and predictive analytics to minimize adverse environmental impacts and toxicity.

Biomass – Any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants, algae, grasses, animal manure, municipal residues, and other residue materials.

- **Sustainable biomass** – Biomass that does not affect food production for domestic consumption or export, does not lead to deforestation or land degradation and maintains environmental quality.

Bioproduction – Biobased production, including biomanufacturing, that uses biological systems, including plants, microbial consortia, individual living cells, and/or parts of living cells (known as cell-free systems), or single or multiple enzymes, to produce commercially important products from biomass feedstocks in a broad range of economic sectors including health, nutrition, agriculture, and industrial applications.

Catalyst – A substance that speeds up a chemical reaction, or lowers the temperature or pressure needed to start one, without being consumed during the reaction.

Feedstocks – Resources used as the basis for manufacturing another product. Most often within the context of this convening, a source of carbon to produce an array of chemicals.

- **Alternative feedstocks** – Renewable feedstocks that are underutilized.
- **Animal coproduct** – Discarded or underutilized material from industries directly associated with the raising and processing of animals and animal products. These include coproducts of animal agriculture (manure, eggshells, used bedding, spoiled milk and milk coproducts, etc.), and meat processing and animal testing (carcasses, bones, feathers, etc.).
- **Circular feedstocks** – Feedstocks derived from waste materials, such as agricultural residues and forest slash; as such, renewable waste from one economic activity becomes the source material for new economic activity.

- **Crop residue** – The portion of the crop remaining after the primary product is harvested or processed. Examples include corn stover (stalks and husks), rice straw, and nut husks and shells.
- **Forestry residues** – Woody biomass left over from wildfire management and timber operations (branches, stumps, treetops, bark, sawdust, wood chips, etc.), and coproducts of industrial wood-processing (bark, sawmill slabs, sawdust, wood chips, etc.).
- **Future feedstocks** – The collective term for both circular and alternative feedstocks, including agricultural residues, forestry residues, municipal solid waste, and processing residues.
- **Lignocellulosic feedstocks** – Plant matter such as trees, grasses, and crop residues after edible portions have been separated. Lignocellulosic material is composed of cellulose, hemicellulose, and lignin, which are the primary components of plant cell walls. Many, but not all, future feedstocks are lignocellulosic.
- **Municipal solid waste** – Waste (garbage) collected from municipalities consisting mainly of yard trimmings, paper products and other organic matter such as food waste.
- **Processing residues** – The coproducts and waste streams produced when biomaterials are processed. For example, sawdust at timber mills, sugar cane bagasse, "black liquor" from pulp and paper production, etc. These materials aggregate at the point of processing.
- **Renewable** – Derived from natural sources that can be replenished at a higher rate than they are consumed.

Products – Intermediate chemicals and end-use products which can be made by transforming feedstocks through various processes.

- **Bioadvantaged molecules** – Molecules derived from biology that have performance advantages relative to those produced from fossil carbon feedstocks.
- **Biobased chemicals** – Chemicals derived from plants and other renewable agricultural, marine and forestry materials.
- **Bioprivileged molecules –** Chemical intermediates derived from biology that can be converted efficiently into diverse chemical products, including both novel molecules and drop-in replacements for petroleum-based products.
- **C1, C2, C3, C4, C5, C6** – Refers to the number of carbon atoms in a molecule. For example, methane, carbon dioxide, and carbon monoxide are all C1 molecules, and ethane and ethylene are examples of C2 molecules. Additional examples are shown in **Figure 2**.
- **Commodity chemicals** – Molecules generally used as intermediates, manufactured, sold, and traded on a global basis whose price is quoted on commodity exchanges such as ICIS. These tend to have high volume and low value, with lower margins.
- **Platform chemicals** – Chemicals that can be produced from circular biomass that serve as important precursors to a wide range of solvents, resins, flavors,

fragrances, adhesives, plastics, etc. Examples include methanol, ethanol, benzene, toluene, xylene, 1,4 butanediol, ethylene, 2,5 furandicarboxylic acid, organic acids (e.g., lactic, succinic, levulinic), etc.

- **Specialty chemicals** – End-use functional molecules that are manufactured to purpose, used as solvents, resins, flavors, fragrances, food ingredients additives, enzymes, etc. These include renewable fine chemicals. These tend to have low volume and profit margins that are significantly higher than commodity chemicals.

Transformational Technologies – Methods or enabling tools for converting feedstocks and intermediate chemicals toward final products or supporting the conversion at critical points throughout the process. Examples include but are not limited to industrial fermentation, biotransformation, pyrolysis, computational modeling, bioprocessing, enzyme design, etc.

Executive Summary

The Foundation for Food & Agriculture Research (FFAR) and Schmidt Futures partnered for a convening to identify strategic research opportunities to advance the circular bioeconomy—an economy that uses waste as inputs and is enabled by advances in biotechnology. The goal of the convening was to identify promising areas of research and development that are underfunded, have potential to yield actionable results in the next five years, and require interdisciplinary collaboration to move the circular bioeconomy forward. To help identify strategic opportunities, fifty diverse stakeholders convened in March 2023 to explore how best to capture value from "future feedstocks": circular and alternative carbon sources for chemicals, plastics, and other products to drive growth of the circular bioeconomy. Future feedstocks include agricultural residues, forestry residues, processing residues, and municipal solid waste to name a few. Through panels and discussion workshops, participants identified the challenges and opportunities of utilizing future feedstocks, technologies to transform them, and products that can be produced from them.

Participants identified several challenges in advancing the circular bioeconomy, many related to 1) the complexity of future feedstocks in terms of heterogeneity, variability, and collection; 2) the high upfront cost to scale-up operations; and 3) the lack of adequate tools, data, and models to inform decision making in the bioeconomy. To address these and other challenges, participants collaborated to identify and prioritize **nine research themes** for further inquiry and investment that could yield high-impact, near-term results for the circular bioeconomy:

1. **Anaerobic Digestion** – This well-understood process excels at processing heterogeneous feedstocks. It can be improved by modifying methanogens (microbes active in the final steps of anaerobic digestion) and pretreating inputs to fully degrade feedstocks prior to processing. There are opportunities to optimize anaerobic digester systems to be more resilient and practical for farmers to use, both economically and logistically, as well as opportunities to find higher-value applications for the resulting biogas, volatile fatty acids, and nutrients that can all be coproducts of anaerobic digestion.

2. **Biological and Chemical Process Linkages** – There is a need to convert heterogeneous feedstocks into a more homogeneous set of molecules (molecular "funneling") or to separate molecules from each other for further processing. Biological and chemical processes will need to be used in tandem to make funneling and separations a reality.

3. **Data and Knowledge Sharing** – Better tools are needed to share and access knowledge in the bioeconomy. These tools could reveal knowledge gaps, relay lessons learned, and make it easy to align feedstock characteristics with the pathways to

convert feedstocks to end products. Improved data and knowledge sharing is a critical step to better coordinating the bioeconomy.

4. **Gas Feedstocks** – Gases (carbon dioxide, carbon monoxide, methane, hydrogen) are convenient intermediates that can be generated from heterogeneous feedstocks via pyrolysis, gasification, and anaerobic digestion. Emerging hydrogen hubs sponsored by the U.S. Department of Energy could also increase the availability of carbon-free hydrogen, ammonia, oxygen, and ozone. New, low-cost, continuously operating reactors are needed to utilize these gases to make useful chemicals, as well as models to predict and optimize the operation of these reactors. A study of gas availability could attract investment in this area.

5. **Homogeneity** – To address the heterogeneity and unpredictability of feedstock quality, "formatted feedstocks" can be created by blending regional biomass resources to defined specifications. This approach would involve collaboration among farmers, aggregators, and industry to define specifications for combining niche feedstocks into the abundant supplies that industry requires.

6. **Modeling** – Improved tools for modeling of future feedstocks can help de-risk investments into further research and development (R&D) and scale-up. Specifically, techno-economic analyses (TEAs) and life-cycle assessments (LCAs) are needed on novel feedstocks and conversion pathways before resources are invested to further develop these feedstocks.

7. **Modularity** – Modular, "cookie-cutter" reactors, which can easily be adapted to specific projects that use distributed feedstocks, can bring down capital costs and accelerate scale-up. Sharing data from these reactors could further help troubleshoot to bring down operating costs.

8. **Regionality** – Improved data and connectivity tools can connect waste biomass with new economic activity by elucidating what feedstocks are available and what infrastructure exists to mobilize them.

9. **Starch Reallocation** – Substituting starch in animal feed with pretreated lignocellulosic feedstocks has the potential to release substantial amounts of starch for use as a superior bioeconomy feedstock. This substitution can be achieved without requiring significant technological advancements or new infrastructure. However, further development of lignocellulosic feed processes, as well as environmental and economic analyses, are necessary.

Background

As the energy transition to renewables progresses, it is also necessary to transition the chemical industry, which produces many of our everyday products, away from fossil carbon. Rethinking how carbon is sourced for products also creates an opportunity to rethink how carbon flows through the economy. Currently, fossil carbon is extracted, refined into products, utilized, occasionally recycled, and eventually disposed of in landfills, waterways, and the atmosphere. This process has a significant impact: plastics and other chemicals accumulate in the environment and the chemical manufacturing industry releases about 3% of greenhouse gas emissions in the United States (U.S. EPA, 2021a). In contrast, a circular bioeconomy that repurposes waste carbon from renewable sources to create high-value products that are used, reused, recycled, and biodegradable is possible. Currently underutilized and waste carbon streams from industry, agriculture, forestry, and cities, are abundant and can be leveraged as future feedstocks without disrupting the food supply. Meanwhile, recent gains in biotechnology and biomanufacturing processes are making it ever more possible to develop these feedstocks into products that are carbon-neutral or even carbon-negative over their life cycle (**Figure 1**). However, a coordinated effort is needed to capture the opportunities of future feedstocks and realize their potential to develop the circular bioeconomy.

There is a wealth of future feedstocks that are currently being wasted, burned for heat, or used in low-value applications. For example, the U.S. Department of Energy (U.S. DOE) estimates that every year over 100 million dry tons of crop residues—predominantly corn stover from the Midwest—could be available in the United States at $60 per ton (U.S. DOE, 2016). Similarly, manure (18 million dry tons per year), orchard trimmings (5 million dry tons per year), and the waste hulls and straw from wheat, oats, almonds, and other crops have significant potential to become future feedstocks (U.S. DOE, 2016). Further, forestry residues may grow in availability due to the USDA's $1 billion investment in wildfire management (USDA, 2023). In 2018, towns and cities in the United States generated 63 million tons of food waste and 67 million tons of paper and paperboard, much of which is sent to landfills (U.S. EPA, 2023). This list is not exhaustive, but aggregating these feedstocks could create value for smallholder farmers while collectively achieving economies of scale for industry. With this abundant supply, the bioeconomy has the potential to replace the 162 million tons[1] of petroleum, natural gas, and coal used each year for non-energy purposes (U.S. EIA, 2023a), while also providing new opportunities for marginalized communities.

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[1] Based on energy densities of 45.5, 53.6, and 30 MJ/Kg for petroleum, natural gas, and coal respectively.

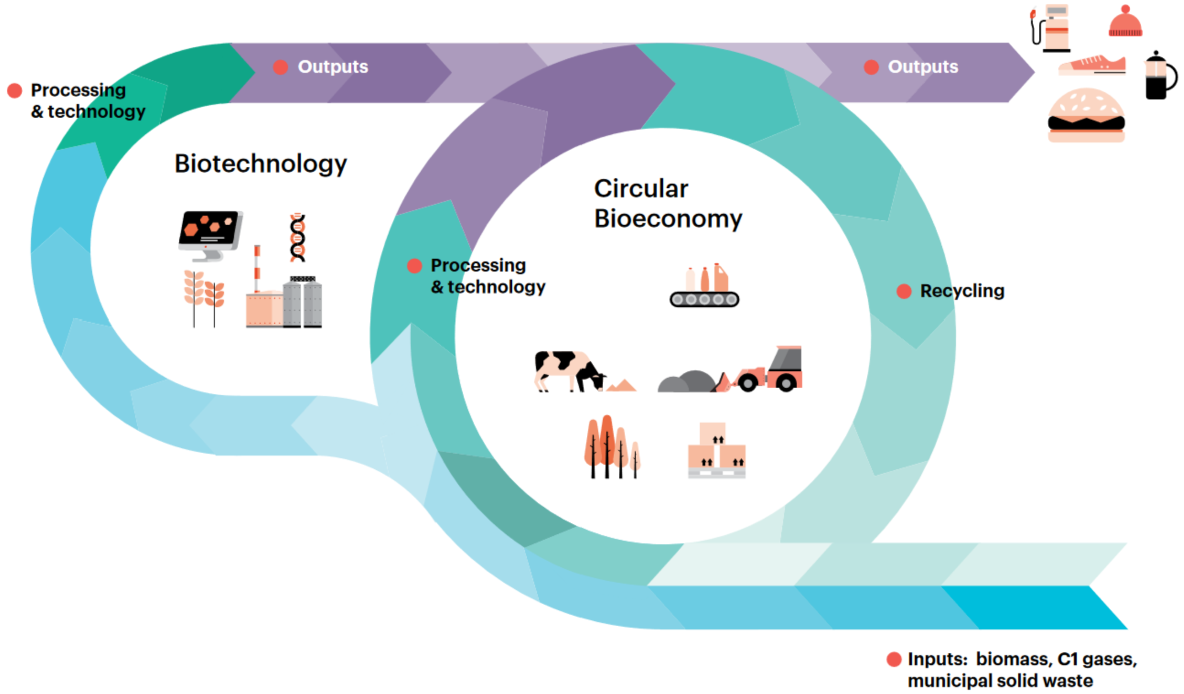

Figure 1. Realizing the Circular Bioeconomy will depend on future feedstock inputs such as waste biomass, C1 gases, and municipal solid waste, as well as advancements from biotechnology to enable these feedstocks to be utilized and converted to an array of products in circular supply chains (Hodgson et al., 2022).

The bioeconomy is showing immense potential for scaling and converting feedstocks into the products that society depends on. These products include molecules equivalent to those produced with fossil carbon feedstocks, as well as bioprivileged molecules—which can be converted into novel chemicals (Shanks & Keeling, 2017)—and bioadvantaged molecules—with performance advantages over fossil-derived molecules. For instance, sugars and plant lignin can be used to produce bioprivileged molecules like muconic acid, triacetic acid lactone, and 5-hydroxymethylfurfural, which can be used to make well-established materials like polyester, polyethylene terephthalate (PET), and nylon, as well as novel environmentally friendly industrial solvents and bioplastics. Bioprocessing can also selectively produce either L or D-lactic acid, resulting in performance advantages in the final polylactic acid (PLA) bioplastic when compared with petroleum-derived lactic acid. The bioplastics sector produced 2.3 million tons of material in 2022, with PLA leading the way (Astute Analytica, 2023). In the near term, bioprivileged molecules are well-positioned to fill the gap in C3, C4, and C5 molecules, which are already challenging to source from fossil feedstocks. In the long term, bioadvantaged molecules could provide improved replacements for many other petroleum-derived products. Policymakers realize this potential and have put renewed emphasis on the sustainable use of biomass to achieve circularity (White House, 2022, 2023). Collectively, these are major steps toward transitioning to future feedstocks to produce products that are reusable, recyclable, and biocompatible.

While future feedstocks offer immense environmental and economic benefits, significant obstacles remain to achieving their potential. The most pressing challenge is the complexity and variability of these feedstocks, which—once brought into bioproduction systems—can disrupt biological processes, deactivate catalysts, and consequently compromise product quality. Furthermore, much of the carbon in future feedstocks (e.g., cellulose, hemicellulose, and lignin) is less biologically accessible than the carbon in starches, sugars, and oils that earlier bioeconomy successes relied upon. The difficulty of collecting and transporting feedstocks only adds to these challenges because many feedstocks cannot be pipelined like petroleum and other liquids. Even the established U.S. ethanol industry struggled to produce the 16 billion gallons of cellulosic biofuel which Congress projected could be blended into fuels by 2022 when it established the Renewable Fuels Standards (RFS[2]) in 2007 (Energy Independence and Security Act, 2007). Instead, the EPA has allowed less than a billion gallons a year of cellulosic biofuel to be sold under the RFS due to a lack of production capacity (U.S. EPA, 2021b). The successful utilization of future feedstocks will require a concerted effort to overcome their inherent complexity, recalcitrance, and cumbersome collection.

Schmidt Futures and FFAR collaborated on this convening with a shared belief that these challenges are sizeable but surmountable. On March 28th and 29th, 2023, they invited bioeconomy leaders from diverse sectors and experiences to convene in San Diego, CA, with the goal of identifying promising lines of inquiry that could accelerate the circular bioeconomy. Representatives from industry, startup companies, universities, national labs, venture capital, trade groups, nonprofits and government funding agencies all attended. Participants drew on their past successes and failures to build a common understanding of the challenges and opportunities that lie ahead for the bioeconomy. Together, they **identified research areas for further inquiry that are currently underfunded, have potential to yield actionable results in the next five years, and require interdisciplinary collaboration**. Throughout the process, participants considered technical, as well as non-technical challenges, to better understand the enabling environment needed to advance the circular bioeconomy.

The convening organizers note that among invited guests, some key stakeholders were unable to attend. They recognize that additional perspectives from the U.S. Department of Agriculture, the National Science Foundation, the U.S. Environmental Protection Agency, academic researchers, and additional industry leaders would have added value, and may have changed the outcome of areas identified for additional research.

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[2] The Renewable Fuel Standard (RFS) program is a national policy that requires a certain volume of renewable fuel to replace or reduce the quantity of petroleum-based transportation fuel, heating oil or jet fuel. There are four categories under which fuels can qualify to meet RFS: Biomass-based diesel, cellulosic biofuel, advanced biofuel, and total renewable fuel.

Introductory Presentations

Welcome & Introductory Remarks

Liz McNally, Executive Vice President of Schmidt Futures, and John Reich, Scientific Program Director at FFAR, kicked off the event to introduce the approaches their respective organizations are taking to advance the bioeconomy.

Schmidt Futures is focused on finding and connecting talented people to solve the world's hardest problems. Specifically, their BioFutures Program aims to catalyze a vibrant, resilient, equitable, competitive, and circular U.S. bioeconomy, in which biological resources are transformed sustainably into food, feed, energy, and biomaterials.

FFAR uses public-private partnerships to fund pioneering research in food and agriculture through competitive grants, direct awards, prizes, and consortia. By partnering in this convening, FFAR aims to enhance its research investments in circular economies and inform its research strategy. More information on the organizers can be found in **Appendix B**.

BioFutures: Circular Feedstocks and Bioproduction

Mary Maxon, Executive Director for the BioFutures Program at Schmidt Futures, introduced participants to Schmidt Futures' approach to identifying opportunities to mobilize talent and better coordinate the bioeconomy. The BioFutures Program released The U.S. Bioeconomy: Charting a Course for a Resilient and Competitive Future in April 2022, which their Task Force on Synthetic Biology and the Bioeconomy and 150 expert interviews guided and informed (Hodgson et al., 2022). That report lays out five strategic pillars for action to better coordinate the circular bioeconomy (**Figure 2**).

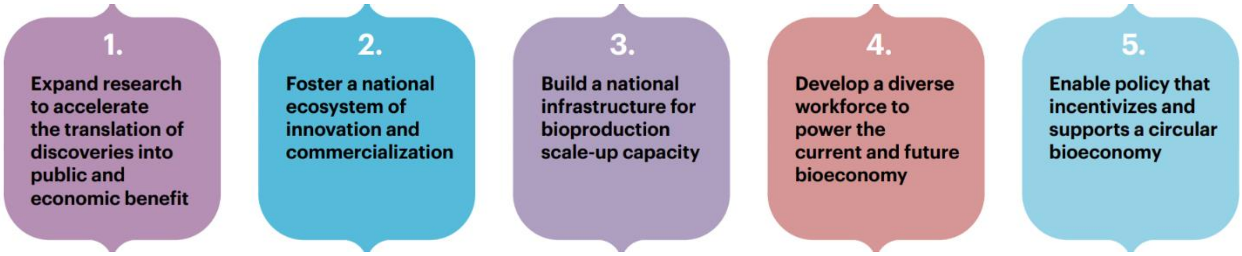

Figure 2. Five strategic pillars for action to better coordinate the circular bioeconomy (Hodgson et al., 2022).

Among other initiatives, the BioFutures Program is working to establish a "Virtual Institute on Feedstocks of the Future (VIFF)," which will develop new scientific approaches to:

- Identify promising future feedstocks.
- Refine technologies and techniques to valorize carbon in future feedstocks.
- Consider broader obstacles to adoption of future feedstocks.

This convening focused on generating and debating research areas relevant to promising future feedstocks that could inform the future VIFF. For the purposes of the convening, Schmidt Futures and FFAR defined future feedstocks as biomass source materials inclusive of circular feedstocks, which come from renewable waste materials, and alternative feedstocks, which are currently underutilized. These feedstocks have the potential to be converted into diverse products through an array of bioproduction pathways as shown in **Figure 3**. Potential sources of future feedstocks include agricultural residues, forestry residues, municipal solid waste, and processing residues.

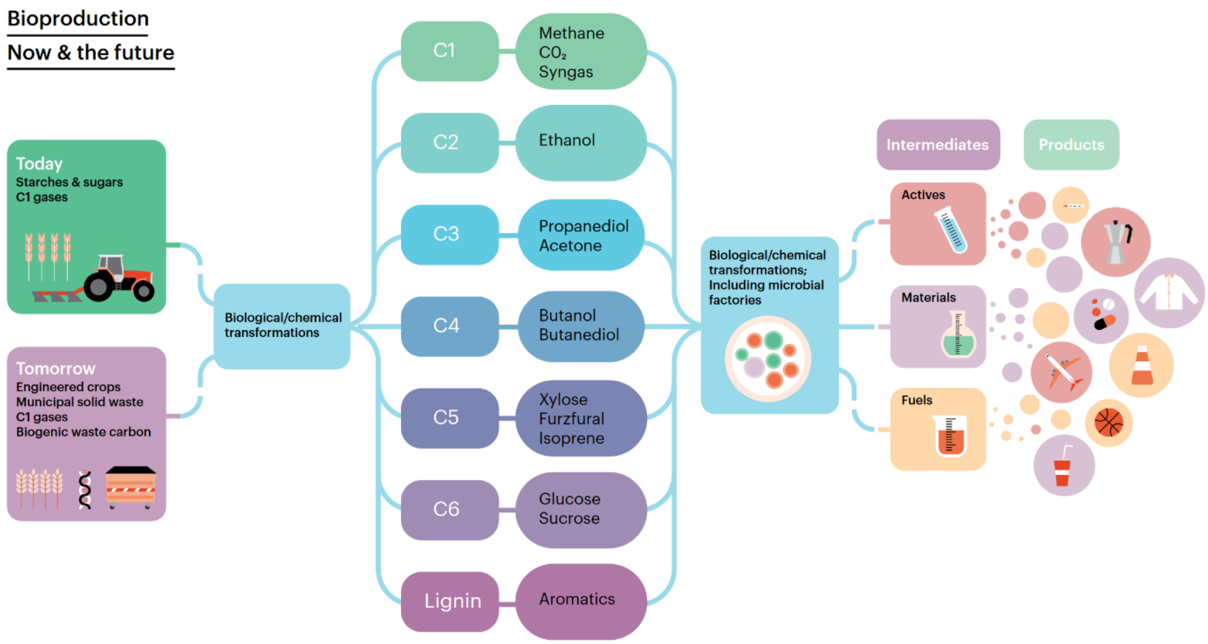

Figure 3. The bioeconomy has the potential to evolve to use a broader range of feedstocks and produce a wider array of products than the petroleum economy. Transitioning to future feedstocks will help enable the circular bioeconomy (Hodgson et al., 2022).

The circular bioeconomy is already advancing on both the R&D and policy fronts. A recent R&D example is the creative use of pulsed-electric fields to extract antioxidants from almond hulls—research that showed that almond hulls could be a useful source of levulinic acid, furfural and 5-hydroxymethylfurfural (Salgado-Ramos et al., 2022). With respect to policy, the White House Office of Science and Technology Policy released "Bold Goals for U.S. Biotechnology and Biomanufacturing" in March 2023. This document mentions circularity, where previous White House releases such as Executive Order 14081 have not (White House, 2023).

Future Biobased Chemical Industry Landscape

Bala Subramaniam, Professor of Chemical and Petroleum Engineering and Director of the Center for Environmentally Beneficial Catalysis at the University of Kansas, provided a recorded presentation to help set the stage for discussions. Detailed content related to this presentation has been published in *ACS Catalysis* (Bellabarba et al., 2023).

Key Takeaways – Future Biobased Chemical Industry Landscape
The energy transition to renewables could create a supply shortfall for many chemicals and products that are coproducts of petroleum refining. Biomass has an opportunity to fill this supply gap. **Reduced petroleum refining would free up platinum, palladium, rhodium, and other metals for use as catalysts in biorefining.** **Hydrogen hubs, which will also produce carbon-free oxygen, will open new opportunities to process biomass using green oxidants.**

The transition to renewable energy and electric vehicles will open new opportunities for the bioeconomy, including a decreased supply of fossil carbon-derived chemicals, increased availability of select metal catalysts, and increased supply of hydrogen and oxidants for biomass processing. As gasoline and diesel demand declines, so will petroleum refining output which will adversely impact the supply of many chemical feedstocks. One such coproduct is naphtha, which can be converted into aromatics and light olefin building blocks that are commonly used to produce plastics, synthetic rubber, and many other products. Some of the falling supply for ethylene and propylene is being met by shale gas sources, but biomass-derived chemicals are also well poised to help meet demand. The transition to electric vehicles will also increase the availability of the metals used in automotive exhaust catalytic converters and used to refine naphtha, including platinum, palladium, and rhodium (Bullock et al., 2020). These metals could be reapplied to the catalytic conversion of biomass feedstocks instead.

Finally, hydrogen hubs, which are expected to receive $8 billion in Federal funding, could also create new opportunities to process biomass into materials such as bio-ethylene and bio-propylene to fill the falling supply from naphtha. Not only will these hubs produce hydrogen, but also carbon-free oxygen which can be used to produce powerful oxidants such as hydrogen peroxide and ozone, which can provide unique ways to convert biomass into feedstocks. Hydrogen peroxide is an especially green oxidant that can be used to make ethylene oxide, propylene oxide, carboxylic acids, polymers, and resins to name a few. Existing petroleum infrastructure could be repurposed to carry out many of these processes with biomass feedstocks. Overall, the energy transition is expected to improve the economics of using and transforming biomass feedstocks on multiple fronts.

Panels

Following the introductory presentations, three panels built common understanding around the challenges and opportunities of using future feedstocks, the transformational technologies that could unlock their potential, and the chemicals and products that can be made from them.

Panel 1 – Future Feedstocks Challenges & Opportunities

Panelists discussed future feedstocks (e.g., lignocellulosic feedstocks, heterogeneous materials, etc.) and the challenges and opportunities of using them. The **Future Feedstocks Workshop** discussed specific feedstocks in greater detail. Panelists included:

- Nichole Fitzgerald, U.S. Department of Energy, Bioenergy Technologies Office (Moderator)
- Tristan Brown, State University of New York (SUNY) College of Environmental Science & Forestry
- Jeffrey Lacey, Idaho National Laboratory
- Andrew Held, Virent

Key Takeaways – Panel 1

To be competitive, future feedstocks will need to be low-cost, available, abundant, predictable, compatible, and sustainable.

Future feedstocks can be a market driver to solve regional challenges. Examples include utilizing wood waste from storm and fire debris, manure that is polluting waterways, and crops planted for remediation.

Regional aggregators could play an important role in connecting farmers to markets, generating volume to give processors predictable supply, and helping to address heterogeneity through quality control and blending.

What makes a good future feedstock?

Panelists discussed the attributes that will enable future feedstocks to be utilized, and generally agreed on the following:

- **Cost** – Needs to be affordable to compete with fossil carbon sources.
- **Available and abundant** – Needs to have reliable volume, ideally year-round, and the feedstock needs to be economically accessible.
- **Predictable** – Many processes can manage feedstock variability and contamination if the variability and contamination are predictable. Predictability is also important for conversion processes (e.g., predictable yield). Climate change may make biomass feedstocks less predictable overall in terms of composition and availability.
- **Compatible** – Needs to be compatible with existing systems.

- **Sustainable** – Needs to provide climate and ecosystem service during its life cycle to make it attractive for stakeholders and policymakers. Future feedstocks should not impact food supplies, like corn ethanol has the potential to do, or there will be roadblocks.
- **Transportable** – Needs to be transportable and safe, for which, converting biomass to simple liquid molecules, such as ethanol and methanol, is an emerging trend.

What are the regional & sustainability considerations?

Local environmental problems can sometimes create new incentives to use future feedstocks. Panelists and participants noted specific examples from their regions:

Manure

- *California* – The state increased incentives to convert manure and other feedstocks to renewable natural gas through its Low Carbon Fuel Standards Program (Jossi, 2021). These policies have yet to be extended beyond fuels.
- *Idaho* – Excrement from dairy feedlots is contributing to nitrate infiltration in the Snake River aquifer. This may lead to additional incentives to treat manure.
- *Wisconsin* – The state is developing a water quality trading market where players can get credit for reductions in phosphorus runoff (Wisconsin DNR, 2020). The market could incentivize the use of manure as a feedstock.

Lignocellulosic waste

- *New York* – Agricultural runoff in the Finger Lakes region has caused harmful algal blooms (HABs). New York institutions are looking at purpose-grown crops as buffers to uptake excess nutrients, mitigate HABs, and serve as feedstocks for displacing fossil carbon sources.
- *California* – A ban on burning agricultural waste is set to take full effect in 2025 and will require producers to find other outlets for their waste biomass (Klein & Vaughan, 2022). In preparation, farmers may look to start connecting this waste to bioprocessing opportunities (Briscoe, 2022).

What are the challenges & opportunities?

Predictable price – Many participants noted how both farmers and feedstock buyers struggle with predictability in prices. Buyers, who are used to getting certain feedstocks for free, can go out of business when farmers start asking for compensation as the market develops. The lack of predictability in the price for biomass is compounded by the volatility of the petroleum with which biomass competes. In combination, the lack of predictability in feedstocks and competition prices creates too much risk to build processing capacity which often requires a 20-year payback period. Similarly, growers of biomass feedstocks need reliable contracting (price and quantity of the feedstocks) to manage supply uncertainties, especially when raising purpose-grown crops.

Heterogeneity – Participants heavily discussed the complex nature of biomass feedstocks during this panel and later in the convening. Two schools of thought emerged for approaching it:

1. The first approach was to embrace diversity and focus on developing solutions that are flexible and can handle heterogeneous feedstocks. Some noted that feedstock agnostic processes have been attempted in the past and most have failed due to unsurmounted technical challenges.
2. The second approach was to focus on specific feedstocks like rice hulls, soybean hulls, and switchgrass, which may be abundant and homogeneous enough individual feedstocks for fermenters to achieve predictable yield.

A compromise may exist between these two approaches in the aggregation of heterogeneous wastes to achieve scale and even out inconsistencies through greater biomass blending.

Collection and aggregation – Many waste biomass streams are cheap and abundant but not readily available due to the challenge of collecting them. Unlike petroleum, which can be pipelined from wells to refineries, biomass is geographically distributed, lower density, and sometimes high in moisture. There is a need to aggregate smaller feedstock sources to make them available for conversion to products at scale, while also ensuring local stakeholders capture some benefit in the process. Aggregation could lead to more efficient collection systems, and address heterogeneity through quality control and blending for consistency. **Panel 3** continued this discussion.

Information – Biomass is traded on local and regional markets, but players need information so the market can react and optimize. Better data are needed on what biomass is available, its quantities and characteristics, and the infrastructure to handle it, so that entrepreneurs can adequately evaluate opportunities for new biorefining operations.

Reusing existing infrastructure – Many regions have existing infrastructure that can be used to dry, process, and store biomass. For example, in the Midwest, many farmers have invested in grain bins and grain dryers to manage their harvest, and these could be used to dry feedstocks and manage variability. However, prospective purchasers of future feedstocks may not have sufficient information to identify where this infrastructure is located or how it can be accessed.

High-value products – Focusing on higher-value products can help offset the cost of managing complex feedstocks. **Panel 3** continued this discussion.

Ready-made feedstocks – Some participants wanted the option to order cellulosic sugar as a commodity with defined specifications. Producing such a commodity has been attempted before but failed. These failures could be better shared and learned from.

Panel 2 – Transformational Technology Challenges & Opportunities

Panelists discussed the key obstacles and opportunities to utilize potential future feedstocks as they relate to transformational technologies (e.g., synthetic biology and fermentation, thermal decomposition, etc.). Convening participants further discussed specific technologies and processes during the **Technology for Identified Feedstocks Workshop**. Panelists included:

- Sarah Richardson, MicroByre (Moderator)
- Gregg Beckham, National Renewable Energy Laboratory
- William Gong, Origin Materials
- Erik Hagberg, Archer Daniels Midland (ADM)
- Deepti Tanjore, Lawrence Berkeley National Laboratory

Key Takeaways – Panel 2

Expanded modeling capabilities are needed to help biorefineries scale and manage feedstock variability across larger regions.

Oxygen content in biomass can be a challenge when trying to make drop-in replacements for petrochemicals, but is also an opportunity to make new bioadvantaged chemicals and biodegradable materials.

Designing bioreactors specifically for the bioeconomy, using low-cost materials, could mitigate the high cost of scale-up.

What are the challenges and opportunities?

Modeling – The ability to model, and therefore predict, what will happen in bioprocessing lags far behind the modeling capabilities of petrochemical processing. As biorefineries scale up, they will source feedstocks from progressively larger regions. As a result, industries relying on future feedstocks will need to predict how variations in feedstock qualities will impact their processes and, more specifically, the fate of contaminants during separations. Ideally, packaged software would be available for purchase, similar to Aspen, but currently available options are not well suited for bioprocessing.

Modeling in the petroleum industry matured as techniques to measure key physical properties of petroleum improved because physical properties are key inputs to models. However, there are barriers to measuring and sharing physical properties of biomass. The national labs focus heavily on measuring physical properties but typically do not publish the results because of private-public partnership agreements. Researchers, in general, rarely publish on physical properties. An exception is Idaho National Laboratory, which publishes a biomass feedstock property library that participants noted is an underutilized resource.

Finally, this panel also discussed the potential for better TEA models. The bioeconomy is full of one-off projects which makes it difficult to predict costs during scale-up (see **Modeling** for further discussion). More standardized reactors could make cost estimating easier and more accurate (see **Modularity** for further discussion).

Oxygen – Unlike petroleum, biomass is rich in oxygen-laden molecules. This oxygen presents challenges in developing biomass-derived drop-in replacements for petrochemicals because it must be removed to create these molecules. However, oxygen-rich molecules could be an opportunity when making new bioadvantaged molecules. Biological processes in the environment may degrade oxygen-rich molecules more efficiently than they degrade petrochemicals, enabling products that are more biodegradable. Pursuing development of novel bioadvantaged chemicals and materials could add regulatory uncertainty for start-up operations but could also lead to higher-value markets.

Scale-up – Bioreactors are one of the drivers for high scale-up costs for the bioeconomy. New equipment designs could use low-cost materials, have better heat transfer at scale, and be tailor-made for nonbiomedical sectors of the bioeconomy. Simultaneously, training is needed for operators to run new bioreactors.

Systems thinking – Product separation from the fermentation broth is generally considered last, after significant investment has already been made to improve fermentation. However, separation is one of the most expensive and challenging steps in the process. Similarly, process development is often focused on the final product, while the coproducts (e.g., microbial biomass, wastewater) can be costly to treat and manage. Thus, startup companies need to plan for multiple bioeconomy sectors to capture the most value.

Benzene, toluene, and xylene (BTX[3]) – BTX could be an opportunity to produce platform chemicals from future feedstocks. The demand for BTX is increasing (approximately 5% per year) as an intermediate for plastics and many other products, which will eventually need a bio-based replacement. It is challenging to use oxygen-laden molecules to make these chemicals, but lignin could potentially be reformed to BTX if catalyst deactivation can be overcome.

Hydrogen – Feedstocks such as hydrogen may be predominantly derived from natural gas due to the cost advantage until cleaner options like renewable-powered electrolysis become economically feasible. As a result, processes designed to be indifferent to their hydrogen source could have prolonged dependence on fossil carbon sources. Biomass can also be used to create a carbon-negative hydrogen where the carbon is sequestered during hydrogen production.

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[3] Benzene, toluene, and xylene (BTX) is a mixture of aromatic hydrocarbons which is historically made from petroleum through catalytic reforming of naphtha but could be made from the lignin fraction of biomass.

Can better access to information help?

Many participants noted information barriers that make it difficult to find what feedstocks are available, find scale-up resources, and learn from others' failures in biomanufacturing. For example, finding the right combination of technologies to process and ferment a specific feedstock, then separate the final product can be challenging. Technical experts at process development units in national labs have struggled to guide entrepreneurs through this process despite extensive knowledge and facilities due to confidentiality agreements. Sharing precompetitive and noncompetitive knowledge could accelerate the success of others by avoiding repetition of past mistakes.

Specifically, there is a need to map the abundance and availability of feedstocks, as well as their characteristics (e.g., adherence to specifications, presence of contamination), to enable better modeling. Similarly, catalogs of available feedstocks and which microbes are ready for production could guide decision making for bioprocessing (see **Data and Knowledge Sharing** for further discussion). Finally, there is also a need to create a culture of sharing failures to move the entire economy forward faster. Many specific data frameworks could help fill the knowledge void.

What are some stories of success?

While participants were eager to have more access to lessons learned from failure, some shared successes which could also be learned from:

- **Scale-up** – Despite a lack of modeling capabilities, automation has improved the ability to scale up reactors. In one example, Ginkgo Bioworks increased its fermentation scale by an order of magnitude within months.
- **Coproduct utilization** – Crude glycerol is a coproduct of biodiesel production, which is 20 to 40% contaminated (e.g., soaps, moisture, and ash). ADM and the Pacific Northwest National Laboratory (PNNL) worked together to scale up the catalytic process to make propylene glycol from crude glycerol for commercial industrial purposes (U.S. DOE, 2018).

In reflecting on successes, one attendee noted that biology is good at handling complexity, while chemistry is good at moving quickly and reliably. Applying this paradigm, biological conversion should be used to convert heterogeneous feedstocks to more homogeneous intermediates for further chemical conversion. For example, anaerobic digestion is good at degrading complex molecules to methane, a common building block that could be further transformed by catalysis or engineered monocultures. Meanwhile, aerobic fermentation is good at degrading some feedstock components that inhibit or pass through anaerobic processes (e.g., lignin). Participants built on this idea during the discussion workshops. It is covered under several research themes discussed later: **Anaerobic Digestion**, **Biological and Chemical Process Linkages** and **Gas Feedstocks**.

Panel 3 – Future Feedstocks & Opportunities for Biobased Chemicals

Panelists discussed identifying potential biobased chemicals of interest to industry and the barriers to producing these. Panelists included:

- Katy Christiansen, Lawrence Berkeley National Laboratory (Moderator)
- Kevin Barnett, Pyran
- Vineet Rajgarhia, Praj Americas
- Karen Warner, BEAM Circular

Key Takeaways – Panel 3

High-value, "bioadvantaged" products can create demand for future feedstocks, helping to overcome the costs of aggregation and feedstock complexity at a scale that is more approachable for startup companies and investors.

Biomanufacturing is well-poised to deliver good-paying, sustainable jobs to underinvested communities.

Startup companies need more flexible testbeds to reach demonstration scale (see Testbeds for Demonstration Scale).

What concerns do you have regarding feedstocks and how does it impact your products?

Similar to **Panel 1**, participants emphasized the importance of feedstock cost, availability, accessibility, and predictability—which are all needed to keep production facilities running year-round. This panel identified accessibility as a major issue for those dependent on furfural (see "Safety" below). Feedstock contamination is also a broad concern, especially when making chemicals (as opposed to fuels) because the catalysts are more sensitive to contaminants.

What are some of the challenges with scaling up processes in the circular bioeconomy?

Testbeds – Various participants highlighted the difficulties in demonstrating their processes at scale before building large-scale production infrastructure. Many startup companies face a chicken-and-egg dilemma: they need to prove they can make products at scale to attract the investment needed to execute the scale-up. To circumvent the issue, companies want testbed sites that can be adapted to validate and de-risk their processes, rather than building demonstration-scale processes from the ground up (see **The Enabling Environment** for detailed discussion).

Collection and aggregation – Participants continued discussion on the need to develop efficient biomass feedstock collection and aggregation systems (continued from **Panel 1**). Feedstocks currently available for free, such as almond tree wood cleared to prevent fire hazards, are available in some communities, but transportation costs are excessively high.

Private or public actors (e.g., industry associations or counties) could establish regional networks to address this issue. In an example local to California's North San Joaquin Valley, BEAM Circular is a non-profit organization facilitating local feedstock aggregation to supply a bioindustrial hub which it is also helping to develop. In other cases, farmer co-ops could aggregate future feedstocks, while preserving smallholder farmers' roles in the value chain. Collection and aggregation costs ultimately affect the real cost of a feedstock.

Experimental trials – Large brands are looking to utilize more sustainable materials but have difficulties finding material suppliers that are willing to adapt their existing production processes to carry out experimental trials. There is a demand for researchers to perform experimental trials to fill the gap. This discussion links with the need for **Testbeds for Demonstration Scale**.

Safety – The stability and reactivity of chemical intermediates are important to consider during scale-up because they can lead to new handling challenges as volumes increase. Safety is a particular concern for those dependent on the intermediate chemical, furfural. Due to environmental regulations and the toxic nature of the production process, most furfural production is currently overseas. The reactive nature of furfural makes it highly expensive to transport to the United States to be refined domestically. As a result, companies relying on furfural may need to establish themselves overseas near furfural production facilities. There is a need to develop the domestic infrastructure for furfural intermediates in a safe way to supply domestic consumers with this intermediate chemical.

What are some of the big opportunities for using circular feedstocks?

Job growth for underinvested communities – Distributed manufacturing has the potential to create good-paying, sustainable jobs, which are hard to find in many communities. While community buy-in is needed, bioprocessing opportunities can attract new investments for communities that have long suffered from underinvestment.

Food waste and food processing waste – Many food processors, restaurants, and cafeterias want to repurpose their waste. Presently, food processing wastes, such as wine coproducts, are often used as animal feed, but they could be used to produce higher-value chemicals and products. Lactic acid, which is used in the manufacture of PLA bioplastic, is an example of a chemical that can be produced from mixed food waste. PLA is already being used as an industrially compostable packaging alternative for takeaway containers and disposable service ware at restaurants. This presents an opportunity to create a circular system where the combined food waste and PLA can be broken down to lactic acid and polymerized back to PLA. Since PLA is durable at lower temperatures, the packaging can be reused several times before being degraded back to lactic acid.

Common intermediates – These can help bridge the gap between heterogeneous feedstocks and processing facilities which need predictability and reduced reliance on starch and sugar. For example, anaerobic digestion can produce methane from heterogeneous feedstocks, which can subsequently be fermented or converted to an array of chemicals and products. Participants built on this concept further during the discussion workshops (see **Anaerobic Digestion**, **Biological and Chemical Process Linkages**, and **Gas Feedstocks**).

Where do you think research priorities should go? Where have we not been investing?

High-value products – Similar to **Panel 1**, participants emphasized the importance of generating high-value products for new ventures to be successful. Historically, there has been a lot of investment in converting lignocellulosic feedstocks to low-value fuels to compete with petroleum at large volumes. However, emerging technologies can generate higher margins by making bioadvantaged products that cannot be made from fossil carbon sources. These products can enter the market at lower volumes which are more approachable for startup companies and investors. Some of the opportunities in this space include developing C3, C4, and C5 chemicals, bioplastics that are both recyclable and biodegradable, and products that make use of the oxygen that is abundant in biomass. All these options present significant potential for creating more circular economies and better returns for investors.

Bioeconomy hubs – Place-based ecosystems are necessary for getting scale, community buy-in, establishing testbeds, and coalescing the talent and resources needed to drive a new industrial revolution. Similar models have been successful with technology hubs, and these successes are being replicated for hydrogen hubs. Mapping the availability of feedstocks could help with siting new biomanufacturing hubs (see **Testbeds for Demonstration Scale** for detailed discussion).

Starch reallocation – Starch is a successful feedstock but feeding starch to ruminants, which can also digest straw and other lignocellulosic materials, is not an optimal use. Substituting pretreated lignocellulosic feedstocks into ruminant feeds could free-up starch for biomaterials and biochemical production (see **Starch Reallocation** for detailed discussion).

Modifying organisms – Biology needs to be pushed to extremes to handle higher pHs and temperatures to operate more efficiently in industrial systems. Genetic engineering, potentially combined with computer modeling, can develop microbes with the qualities needed for efficient conversion of future feedstocks.

Discussion Workshops

The convening held discussion workshops between panels to identify promising lines of inquiry that could accelerate the use of future feedstocks in a circular bioeconomy. The first two discussion workshops, **Future Feedstocks Workshop** and **Technology for Identified Feedstocks Workshop**, focused on generating a mix of ideas through "world café"-style discussion groups with frequent participant rotations to maximize participant interactions. Finally, the **Research Theme Refinement Workshop** focused on coalescing the research ideas surfaced during the initial discussion groups into common research themes and defining what could be accomplished under each theme within the next five years. The guiding questions for each discussion workshop, as well as the format of the discussions, are shown in **Table 1**.

Table 1. The three discussion workshop topics, guiding questions used to facilitate discussions, and the format of the discussion workshops.

Future Feedstocks Workshop	Technology for Identified Future Feedstocks Workshop	Research Theme Refinement Workshop
Guiding Questions What future feedstocks hold potential promise? What are the obstacles and challenges to using potential feedstocks? How do we overcome those obstacles? **Consider:** How can we meet potential regional and/or national needs for utilizing circular feedstocks and where can we have the most impact? What products should we consider for transforming these feedstocks?	**Guiding Questions** What are the most promising technologies and research opportunities to help us overcome the major obstacles identified for these feedstocks? If technologies exist, why aren't they being used? What are the barriers to overcome? **Consider:** What scale do these technologies need to perform? What are the challenges for the technologies of interest and how can we overcome them?	**Guiding Questions** Are there commonalities across scenarios? Is there a regional application? Does this fit within a 5-year window of opportunities? Is this type of work being funded elsewhere (e.g., by U.S. Government)? Are there challenges that cannot be addressed by research?
Discussion Format World Café: small groups, mixed every 30 minutes.	**Discussion Format** World Café: small groups, mixed every 30 minutes.	**Discussion Format** Large group refinement followed by small groups.

Future Feedstocks Workshop

Participants worked in small groups, consisting of varied expertise, to identify challenges and opportunities for utilizing future feedstocks using the guiding questions in **Table 1**. Challenges and opportunities emerged that are common to many feedstocks, as highlighted in **Table 2**. Specific challenges and opportunities for each feedstock are shown in **Table 3**.

Table 2. Common challenges and opportunities identified through the Future Feedstocks Workshop.

Common Challenges	Common Opportunities
Feedstock complexity • Participants reiterated challenges with heterogeneity (see **Panel 1**). • Lignin slows biodegradation in lignocellulosics and needs to be converted to higher-value products to incentivize its separation. **Collection and volume** • Participants built on discussions in **Panel 1** and **Panel 3**. **Temporal availability** • Many feedstocks are only available part of the year, but processing plants need to keep running year-round to justify capital expenditures (CapEx). **Niche resources** • Some feedstocks are not abundant enough to achieve economies of scale on their own. **Cheap competition** • It is difficult to compete economically with cheap fossil carbon sources when using future feedstocks.	**Some future feedstocks are already collected and aggregated** • This can overcome the common challenges in sourcing feedstocks. **Some feedstocks have an environmental cost if not treated (e.g. manure, municipal solid waste, food waste)** • Better valorizing these feedstocks in the bioeconomy can help sustain competition against petroleum-based feedstocks (see **Panel 1**, Regional and Sustainability Considerations)

Table 3. **Future Feedstocks Discussion Workshop: Participants worked in small groups to identify candidate future feedstocks and the challenges and opportunities of utilizing them.**

Challenges	Opportunities
Lignocellulosic Waste Broadly (e.g., hulls, soybean residue, corn fiber, bran)	
• Only available during part of the year. • Short duration before spoiling if untreated. • Inconsistent quality of raw materials. • Biodegradation is difficult. • Insufficient supply to provide economies of scale for niche products.	• Already collected and aggregated in many situations. • Conversion to methane may be a realistic intermediate.
Almond hulls and shells	
• Wet, needs to be processed quickly. • Only available half the year. • Niche. Is there enough volume?	• Already used to produce platform chemicals and large integrated facilities exist for large-volume processing.
Sugarcane bagasse	
• Wet, needs to be processed quickly. • Only available half the year.	• Already used to produce platform chemicals and large integrated facilities exist for large-volume processing.
Forest residuals	
• Often located far from processing facilities.	• Currently being paid (approximately $30/ton) for harvesting and disposal.
Methane and biogas	
• Need large digesters due to slow production rates. • Need to transport inputs to locations where the methane or biogas can be used. • Compete with low-cost natural gas. • Often flared or wasted.	• Can be common intermediates. • Climate benefit to using them. • Low-cost input for aviation fuel. • Solve a waste problem for dairy.
Dedicated energy crops	
• May increase environmental impact.	• Can be grown on marginal or repurposed land. • Can be grown for bioremediation.
Municipal solid waste	
• Highly heterogeneous.	• Already collected in cities. • Available year-round.
Food waste	
• High moisture content (approximately 75%). • Highly heterogeneous.	• Readily degradable. • Available year-round.
Sweet sorghum	
• Only available part of the year. • Needs to be processed right away.	• Create both sugar stream and high yield of biomass. • Suited to a range of growing conditions.

Challenges	Opportunities
Cotton seed hulls	
• Niche and has questionable scalability.	• Not generally used for other applications like animal feed.
Carbon dioxide gas	
• Electrocatalysis and hydrogen gas are needed as inputs to utilize.	• Use could yield carbon credits. • More products could be developed from fermentation where carbon dioxide is a coproduct. • Forthcoming hydrogen hubs could provide the hydrogen needed to reduce carbon dioxide.
Starch reallocation	
• Need to transition animal feed to lignocellulosic materials to free up the starch supply.	• There is existing infrastructure for handling and processing. • Quickly degradable to an array of products. • Readily available.
Lipids and oils from plants	
• Expensive. • Often utilized in the food chain.	• Known conversion pathways.

Technology for Identified Feedstocks Workshop

Participants built on the future feedstocks discussion by identifying technologies that can enhance the uptake and conversion of those feedstocks, using the guiding questions in **Table 1**. Working in small groups, participants identified high-impact technologies and challenges and opportunities associated with those technologies. Through the process, common challenges and opportunities emerged that apply to many of the technologies as highlighted in **Table 4**. Specific challenges and opportunities for each technology are shown in **Table 5**.

Table 4. Common challenges and opportunities identified through the Technology for Identified Feedstocks Workshop.

Common Challenges	Common Opportunities
High CapEx for scale-up is being driven by expensive bioreactors (see Panel 2, "Scale-up," for detailed discussion). **Catalyst deactivation:** • Catalysts are fouled by side reactions. • Catalytic technology is especially critical for C3 to C6 chemicals. • Catalytic systems are needed to convert biological intermediates to final products. This requires connecting biology and chemistry, but these disciplines are often siloed (see **Biological and Chemical Process Linkages** for detailed discussion).	**Modular systems have the potential to bring down the costs of scale-up.** • Repeated systems could reduce engineering and manufacturing costs. • Standardizing unit operations and equipment could lead to more transferable lessons and bring down operating costs. • Modular systems could enable distributed processing to ease collection. **Conversion to common gas intermediates could mitigate catalyst deactivation but is unlikely to completely solve the issue.** • Many complex feedstocks can be feasibly converted to gases (e.g., carbon dioxide, carbon monoxide, methane, and hydrogen) via anaerobic digestion, pyrolysis, and gasification. • These could be intermediates for producing a wide variety of products.

Table 5. Technology for Identified Future Feedstocks Workshop: Participants worked in small groups to identify the challenges and opportunities with technologies to utilize feedstocks.

Challenges	Opportunities
Anaerobic digestion	
• High CapEx/low residence time. • High maintenance and safety risks. • Requires abundant feedstocks. • Does not degrade all of the biomass feedstock, requiring further disposal. • Produces significant carbon dioxide.	• Handles wet biomass. • Can produce volatile fatty acids as a coproduct. • Methanogens could be engineered to break down more complex feedstocks. • Can produce PHA bioplastics. • Could generate carbon credits.
Gasification and pyrolysis	
• High CapEx. • Feedstocks need to be dry.	• The resulting syngas is a flexible feedstock.
Ammonia freezing expansion (AFEX), pretreatment of biomass	
• Has yet to be widely scaled. • High CapEx and safety concerns.	• Can build off existing research. • Can address diverse types of feedstocks.
Homogenization	
• Particle size reduction is energy intensive. • Homogenization at the molecular level (molecular “funneling”) is undeveloped/theoretical.	• Can help overcome issues with pyrolysis. • Can put all of the carbon on the same level.
Steam treatment	
• High CapEx. • Requires safety measures.	• Makes feedstocks more uniform for use in later steps.
Biomass fractionation	
• Underdeveloped/theoretical.	• Can help overcome issues with pyrolysis.
Electrochemistry	
• Largely undeveloped. • Need to get biomass dissolved into a liquid phase.	• Relatively unexplored. Could be combined with hydrogen gas to make new processing opportunities.
Fermentation with carbon capture and storage	
• High CapEx.	• Could generate carbon credits.
Lignin utilization	
• Underdeveloped, but certain technologies are getting to the market.	• Feedstocks are abundant.

CapEx = capital expenditures; PHA = polyhydroxyalkanoate bioplastic

Research Theme Refinement Workshop

Participants built on the prior discussion workshops by prioritizing lines of inquiry and then sorting them into nine research themes which showed promise to advance the use of future feedstocks in the bioeconomy within five years. For each research theme, a group of participants prepared a high-level outline of a potential research program centered around that theme, considering potential research outcomes, the 5-year potential, region of the research, and expertise needed. The subsequent report sections and **Tables 6-Table 14** summarize these discussions and potential research outcomes identified for each of the nine research themes in alphabetical order. The full process of identifying and refining research themes is described in **Appendix D**.

Anaerobic Digestion

Anaerobic digestion is well-equipped to handle complex feedstocks, it is well-understood, and anaerobic digestion reactors are already operating at farms and wastewater treatment facilities. The biogas produced from anaerobic digestion (a mixture of methane and carbon dioxide) could be further processed into an array of products (a focus of the **Gas Feedstocks** theme). Improving anaerobic digestion through technological advances in the pretreatment of feedstocks, optimization, automation, and extraction of coproducts could quickly advance the circular bioeconomy.

Table 6. Anaerobic Digestion: Research needs that are achievable in the near term and can significantly advance the circular bioeconomy.

Research Needs	• Downscaled and automated digesters for farmers to use. • Improved sensors and algorithms to help troubleshoot problems. • Optimized feedstock pretreatment for more effective liquification of solids and resilience with diverse feedstocks. • Optimized nutrient and coproduct (volatile fatty acid) extraction. • Genetically modified microbes for faster, more resilient, digestion. • Biogas converted to new products. • Systematic review of prior research and lessons learned.
5-year Potential	• These outcomes are achievable within 5 years, except possibly microbial engineering.
Region	• Near waste sources, especially dairy.
Expertise Needed	• Microbiology, genetics, engineering (chemical, mechanical, civil, biosystems), biochemistry, TEA/LCA modeling, waste management.

LCA= life-cycle analysis; TEA = technoeconomic analysis.

Biological and Chemical Process Linkages

Biological and chemical processes offer different challenges and advantages in the context of a circular bioeconomy. While biology can excel at handling complexity, chemistry can process homogeneous starting materials quickly and reliably. A circular bioeconomy will need to leverage biological and chemical processes in tandem. Specifically, there is a need to develop selective, feedstock-agnostic, methods to separate biomass component molecules like lignin, hemicellulose, and cellulose or convert these molecules into homogeneous intermediates (molecular "funneling"). Developing and refining these processes could enable the overall conversion of future feedstocks into high-quality platform chemicals and other products for use in the bioeconomy.

Table 7. Biological and Chemical Process Linkages: Research needs that are achievable in the near term and can significantly advance the circular bioeconomy.

Research Needs	• Ability to separate lignin, hemicellulose, and cellulose. • A method of molecular funneling to convert regional heterogeneous resources into homogeneous feedstocks; high-quality platform carbohydrate derivatives and useful lignin substrates that can be used for biobased chemicals. • Pathways to valorize furfural and hemicellulose to new products. • Novel processes that use biological and chemical catalysis in tandem to take advantage of the strengths of each.
5-year Potential	• Bench-scale candidate process(es) can be identified, accompanied by TEA and LCA with a clear path to pilot-scale development.
Region	• Applicable to regions where there are aggregated, under-utilized, or niche cellulosic feedstocks such as hulls and processing waste from nuts, soybeans, and rice.
Expertise Needed	• Biology, chemistry, chemical engineering, economics, catalysis material science, marketing, and social science.

LCA = life-cycle analysis; TEA = technoeconomic analysis.

Data and Knowledge Sharing

Improved tools are needed to effectively share data and knowledge to unlock opportunities in the bioeconomy. Such tools could connect novel conversion pathways with the feedstocks needed to supply them and provide accurate cost-estimating data to vet their economic feasibility. Improved data and knowledge sharing would better coordinate the bioeconomy and catalyze gains in other themes such as **Regionality**, **Homogeneity**, **Gas Feedstocks**, and **Modeling**.

Table 8. Data and Knowledge Sharing: Research needs that are achievable in the near term and can significantly advance the circular bioeconomy.

Research Needs	• A globally accessible database portal that captures what is known and where the knowledge gaps are (e.g., a prototype tool with a UI/UX, and data attributes all informed by user stories). • A tool for researching feedstock conversion pathways and feedstock inventories to help identify end-to-end opportunities. • Datasets to inform better TEA for more accurate cost-estimating.
5-year Potential	• All the above could be achieved in the next five years.
Region	• Data would be stratified by region, state, county, and locality.
Expertise Needed	• Data science and informatics, web development, UI/UX, research analytics, process engineering, farming, and potentially machine learning.

Gas Feedstocks

Heterogeneous waste streams can be converted to gases (e.g., carbon dioxide, carbon monoxide, methane, and hydrogen) via pyrolysis, gasification, and anaerobic digestion. These gases could be combined with the waste gases produced now by industry and the future gases produced by hydrogen hubs (e.g., hydrogen, ammonia, oxygen, and ozone) as they are built out with Federal investment (U.S. DOE, 2022). Advances in reactor design, controls, microbial processing, and modeling could all support the utilization of these gas feedstocks to make simple, homogeneous and transportable liquid intermediates such as methanol and ethanol, as well as higher-value products. Utilization of gas feedstocks can be further enabled by improvements to **Anaerobic Digestion** to produce biogas, and the identification of pathways as discussed in **Data and Knowledge Sharing**.

Table 9. Gas Feedstocks – Research needs that are achievable in the near term and can significantly advance the circular bioeconomy.

Research Needs	• Reduced CapEx via low-cost, high gas-liquid transfer bioreactors. • Research infrastructure for gas fermentation. • New microbial processes developed to valorize waste streams via pyrolysis and gasification. • A study of the industrial use of microbes for C1 gas conversion and product synthesis, and a map of metabolic outcomes of C1 gases. • Hydrodynamic models for three-phase systems (solid-liquid-gas). • Process control schemes for continuous operation systems. • Map of gas sources throughout the United States.
5-year Potential	• All the above outcomes are achievable within 5 years.
Region	• Near coal mines, steel mills, paper mills, agriculture/ animal operations, landfills, and green electricity hubs for hydrogen production.
Expertise Needed	• Biology, biochemical engineering, market research and supply chain modeling, downstream processing, computational science.

CapEx = capital expenditures; C1 = single carbon molecule (e.g., methane, carbon monoxide, carbon dioxide).

Homogeneity

Biomass heterogeneity, availability, and variability remain key challenges to utilizing future feedstocks. A practical approach is to aggregate and preprocess biomass into predictable blends ("formatted feedstocks"), specific to each region, which can match the quality and reliability in supply that industries need. This approach will require collaboration among farmers, aggregators, and industry and can be kick-started by taking an inventory of biomass, as proposed in the **Regionality** theme.

Table 10. Homogeneity: Research needs that are achievable in the near term and can significantly advance the circular bioeconomy.

Research Needs	• Defined feedstock formats that can bridge what farmers produce with what industry needs. "Formatted feedstocks" would be a regional blend of resources preprocessed to meet a consistent specification. This could be achieved through the following phases: ○ A pre-study to identify ten candidate regions for formatting. ○ Preliminary study of formatted feedstocks in those regions with stakeholder engagement and interviews. ○ Lab-scale production of formatted feedstocks and conversion to end products. ○ De-risking and scale-up phase. ○ Demonstration projects. • Map and quantification of the availability of the formatted feedstocks. • An economic analysis of utilizing formatted feedstocks. • A transparent map of the supply chain for all players.
5-year Potential	• Some regional niche feedstocks could be mobilized quickly in 5 years.
Region	• Feedstock formats would be unique to each region.
Expertise Needed	• Agriculture, process/conversion science, economics, stakeholder engagement, community participation.

Modeling

TEA and LCA are needed for novel feedstocks and novel conversion pathways. While these models are well established for existing feedstocks, they can be instrumental in informing early R&D investments to valorize future feedstocks. Participants consistently identified improved TEA, LCA, and other types of modeling as research needs in other themes. Improved modeling efforts will depend on better data sets that participants identified in the **Data and Knowledge Sharing** and **Regionality** themes.

Table 11. Modeling: Research needs that are achievable in the near term and can significantly advance the circular bioeconomy.

Research Needs	• Predictive analytics for feedstock cost & availability in different areas (LCA/TEA) that can inform future investment into niche feedstocks.
5-year Potential	• Widely modeling future feedstocks is achievable within 5 years. It is also notable that AI-assisted novel pathway design is possible but may take longer than 5 years.
Region	• Flexible models can be adaptable to all regions.
Expertise Needed	• Engineering (civil and environmental), systems analysis, computational modeling, chemistry, biology.

LCA = life-cycle analysis; TEA = technoeconomic analysis.

Modularity

New bioprocessing operations are capital intensive, in part because bioreactors and other systems are custom engineered and built for each project. It is not unheard of for two-thirds of the capital cost to go toward reactors when scaling up new facilities. Making modular “cookie-cutter” systems that are useful for common processes, yet adaptable to specific needs, could significantly reduce engineering and equipment costs. In turn, more affordable reactors can make the bioeconomy more approachable to investors.

Table 12. Modularity: Research needs that are achievable in the near term and can significantly advance the circular bioeconomy.

Research Needs	• Market-ready, cookie-cutter systems which can be adapted to regional needs to save time and money on design and construction. • Data sharing between modular systems for better troubleshooting during operation.
5-year Potential	• Cookie-cutter reactors could be designed, prototyped, and beginning to be used to demonstrate the conversion of feedstocks to end-use products.
Region	• Adaptive to all regions.
Expertise Needed	• Engineering (chemical, mechanical, civil, etc.), bioprocessing industry, molecular biology.

Regionality

A platform is needed to connect available feedstocks, infrastructure, and institutions in each region with emerging biotechnologies. This platform could significantly reduce the time and effort to evaluate new opportunities. Similar to **Data and Knowledge Sharing** and **Gas Feedstocks**, this theme focuses on inventorying feedstock availability.

Table 13. Regionality: Research needs that are achievable in the near term and can significantly advance the circular bioeconomy.

Research Needs	• A nationwide marketplace/platform, which connects players to make use of feedstocks. Players may include feedstock producers, harvesters, and purchasers. • An inventory of biomass availability, along with relevant infrastructure and socioeconomic factors to validate new opportunities: ○ Existing biomass storage and processing infrastructure. ○ Proximity to rail and other necessary services. ○ Innovation assets and educational institutions.
5-year Potential	• Platform could be entirely built in approximately 2 years. • Ownership by a national lab could make it nimble.
Region	• Across the United States but can be started in select regions where data is most available.
Expertise Needed	• Chemical industry, data analytics, feedstock owners/supply side, user interface design, economic development (e.g., state development entities, National Association of Counties, National Association of State Energy Officials), geographical information systems, national labs.

Starch Reallocation

Starch is a readily degradable feedstock with abundant collection and processing infrastructure, but almost half of U.S. corn production is used for animal feed (USDA ERS, 2022). This feed could be replaced with pretreated lignocellulosic biomass, which ruminants are more adept at digesting, allowing starch to be reallocated to biobased chemical production. Using pretreated lignocellulosic biomass for feed has been well-researched, although barriers remain to widespread adoption. Reallocation of starch feedstocks has the potential to lower the price of grain, give animals healthier lives, reduce methane emissions from agriculture, and improve the image of corn for consumers.

Table 14. Starch Reallocation: Research needs that are achievable in the near term and can significantly advance the circular bioeconomy.

Research Needs	• Replicate the meat quality of animals raised on starch-based feed in animals raised on lignocellulosic-based feed, in trials with technical assistance for farmers. • Develop treatments to convert lignocellulosic biomass to feed for non-ruminants (e.g., swine). • Define the potential of products from reallocated starch. • Compare methane emissions: pretreated lignocellulosic feed vs. starch feed. • Analyze the economic impact of pretreated lignocellulosic feed for cattle.
5-year Potential	• Many outcomes are achievable within 5 years. • Farmer outreach through agricultural extension agents will be key. • Would need to identify and cultivate starch usage by the biochemical industry.
Region	• Midwest (Great Plains) in the vicinity of ethanol plants.
Expertise Needed	• Animal feed and ruminant nutrition, bioconversion, systems-based/big picture thinkers, LCA/TEA, rural sociology, agricultural extension agents.

LCA = life-cycle analysis; TEA = technoeconomic analysis.

The Enabling Environment

While the convening focused heavily on technical challenges and opportunities, many participants also identified non-technical challenges which impact the adoption of biobased chemicals from future feedstocks. Participants discussed these factors in **Panel 3**, but also throughout discussion workshops. Specifically, participants focused on policy and the need for testbed infrastructure.

Policy

Factors for Policymakers

Participants placed a heavy focus on policy when discussing the enabling environment for producing materials and chemicals from future feedstocks. Participants broadly agreed that policies that incorporate externalities into the market could create more economic incentives to utilize future feedstocks. For example:

- **Eutrophication and HABs** – Usually caused by the release of nitrogen and phosphorus, the cost of eutrophication and HABs is largely borne by water treatment utilities rather than those that release nutrients into the environment through manure and wastewater treatment. Recovering these nutrients is especially important to our "fertilizer independence" since the United States depends on phosphorous imports. Producers would likely pay more to dispose of manure if their operations included environmental costs.
- **Chemical fuel parity** – Most policies, like the RFS, do not account for the large carbon impact of chemical production, which intersects with fuel production. Either including chemicals in these policies or switching to policies that are outcome-oriented (e.g., total carbon reduction) could more broadly incentivize the market.
- **Feedstock parity** – Even in the context of fuels, U.S. policies lack flexibility. For example, biomass that is cleared for fire prevention efforts in national forests does not qualify as a feedstock for cellulosic biofuels under the RFS (Energy Independence and Security Act, 2007). While the U.S. Congress originally intended for these rules to protect forests from being overexploited, they could be modified to incentivize the connection of excess biomass from wildfire management efforts to new market opportunities.
- **Plastics** – The end-of-life of each product needs to be considered. Incentives to reduce the complexity of municipal solid waste could make it easier to recover value from this highly heterogeneous waste source. For example, a penalty for producers using hard-to-recycle plastics or multilayer materials could help pay for sorting efforts. Plastics also rely heavily on the leaky natural gas infrastructure which releases the greenhouse gas methane. The methane fee within the Inflation Reduction Act of 2022 is the first time the natural gas industry is having to pay for these emissions (Inflation Reduction Act, 2022).

- **Regionality** – **Panel 1** noted how feedstocks are highly regional, however, U.S. DOE's funding strategies do not currently focus on regional and niche opportunities. Instead, U.S. DOE prioritizes national-scale opportunities (approximately 10 million gallons per year scale of fuel or chemical generation), requiring that lessons learned in one region need to be transferable to others. As a result, unique and valuable regional opportunities may be getting underinvested in.
- **Gases** – There is a general lack of infrastructure to safely handle gaseous feedstocks such as ammonia, oxygen, biogas, syngas, hydrogen, and other products. These feedstocks offer several advantages and there may be strategic opportunities to improve the transport of these gases as federal investment goes toward hydrogen hubs and infrastructure improvements.
- **Furfural** – There is a need to onshore furfural production back to the United States. There are many opportunities for transforming furfural to higher-value products, but production has been offshored mainly due to the challenging nature of furfural and our stringent environmental and safety regulations. There is an opportunity for private-public partnerships to onshore furfural production back to the United States safely and effectively.

Testbeds for Demonstration Scale

Factors for National Labs, Funding Agencies, and Local Business Development

Many participants had been through the scale-up process and noted how difficult it is to test their processes affordably at progressive scales, especially in the 10,000-to-100,000-liter range. Startup companies need the ability to demonstrate at scale and identify unforeseen obstacles as they grow, and several testbed facilities have been established in the United States to help fill this role (listed in **Appendix C**). However, these facilities are more expensive than their counterparts abroad and restrict users from selling products which is a key metric of success for investors. Further, many of these facilities do not have the ability to handle gas feedstocks as they are designed predominantly for fuel production and liquids instead of chemicals or gases, which require specific handling methods. Testbeds abroad are often less expensive to use, have lower overhead, many do not expect ownership in intellectual property, and they typically negotiate and finalize contracts faster than existing U.S. testbeds. As a result, many testbeds in the United States are not being utilized. Non-profits like BEAM Circular are working to fill the gap by developing regional test beds in California, but there is still a lot of room for improving the testbed infrastructure already in place. Data generated by research under the **Data and Knowledge Sharing** and **Regionality** themes could inform siting of new testbeds.

Conclusion

The convening panel discussion and discussion workshops identified many challenges and opportunities to advance the circular bioeconomy through future feedstocks. Three over-arching challenges stood out: 1) the complexity of feedstocks both in their composition (e.g., heterogeneity) and their variability, 2) the high cost of scale-up, and 3) the challenges of informed decision making, mainly due to undeveloped modeling capabilities and difficulty finding data. Participants worked together to develop nine research themes for further inquiry which can address these challenges and others to accelerate the circular bioeconomy over the next five years. **Table 15** summarizes these research themes.

During the discussion workshops, groups working under different research themes reached similar or complementary ideas on where to invest R&D resources. For example, four groups all discussed a similar vision of mapping and inventorying feedstock availability to help better connect the market (**Data and Knowledge Sharing**, **Gas Feedstocks**, **Homogeneity**, and **Regionality**). Some themes are well-positioned to enable advancements in other themes. For instance, the **Anaerobic Digestion** theme focused on reliably producing biogas from a wide range of feedstocks, while the **Gas Feedstocks** theme focused on converting gases to higher-value products. Similarly, the **Regionality** theme focused on identifying what feedstocks are available where; information that could be used to identify the "formatted feedstocks" possible for each region, as envisioned under the **Homogeneity** theme. Finally, most themes included discussion about **Modeling** as a tool to enable near-term gains. In all, the interconnection of these themes reflect the interconnectedness of the industry, and the need for better coordination to catalyze growth of the circular bioeconomy.

Participants noted multiple factors, beyond research and technical challenges, which form **The Enabling Environment** that the circular bioeconomy must grow within. The need to account for the full cost of waste in the environment and the need for policies that incentivize outcomes rather than prescribe solutions. The scale-up environment was a ubiquitous challenge for start-up companies, with many suggesting improvements for the nation's testbed infrastructure. Despite these challenges, participants noted that the economic opportunities are promising for bioadvantaged products, and there are ripe opportunities for private, public, and non-profit organizations to catalyze growth in the bioeconomy.

Table 15. A summary of near-term potential research outcomes (shown as bullet points) for each research theme (each row of the table), that small groups developed in the refinement workshop. The research outcomes (table body) are organized under the major challenges (each column) they address.

Research Theme	Major Challenges Feedstock Complexity	Scale-up Costs	Informed Decision Making
Anaerobic Digestion	**Blend and Preprocess Feedstocks** • Optimized for resilience amongst an array of feedstocks. • Optimized pretreatment for more effective liquification of solids. **Improve Established Processes** • Optimized nutrient and coproduct (e.g., volatile fatty acid) extraction. • Genetically modified microbes for faster, more resilient, digestion. **Develop New Tech** • Pathways to convert biogas to new chemicals and products.	**Reactor Design** • Downscaled and automated for farmers to use.	**Algorithms** • Improved sensors and algorithms to help troubleshoot problems. **Directed Study** • A systematic review of prior research and lessons learned.
Biological and Chemical Process Linkages	**Develop New Tech** • Ability to separate lignin, hemicellulose, and cellulose. • A method of molecular funneling to convert regional heterogeneous resources into homogeneous feedstocks; high-quality platform carbohydrate derivatives and useful lignin substrates that can be used for biobased chemicals. • Pathways to valorize furfural and hemicellulose to new products.		**Models** • Better LCA and TCA tools to validate process sustainability.

	Major Challenges		
Research Theme	**Feedstock Complexity**	**Scale-up Costs**	**Informed Decision Making**
Data and Knowledge Sharing			**Data Frameworks** • A portal that captures knowledge and knowledge gaps with a quality UI/UX. • A tool for researching feedstock conversion pathways and feedstock inventories. • Datasets to inform better TEA.
Gas Feedstocks	**Improve Established Processes** • Enhanced gas-liquid transfer in bioreactors to utilize syngas made from complex feedstocks. • Additional microbial processes to valorize waste streams via pyrolysis and gasification.	**Reactor design** • Reduced CapEx via low-cost, high gas-liquid transfer bioreactors.	**Models** • Hydrodynamic models for three-phase systems (solid-liquid-gas). **Algorithms** • Process control schemes for continuous operation systems. **Data Frameworks** • Map of metabolic outcomes of C1 gases. **Directed Study** • Map of gas sources throughout the United States. • A study of industrial microbial chassis for C1 gas conversion and product synthesis.
Homogeneity	**Blend and Preprocess Feedstocks** • Defined feedstock formats that can bridge what farmers produce with what industry needs. "Formatted feedstocks" would be a regional blend of resources pretreated to meet a consistent specification.		**Directed Study** • Map and quantification of the availability of the formatted feedstocks and the resources that feed into them. • An economic analysis of utilizing formatted feedstocks. **Data Frameworks** • A transparent map of the supply chain for all players.

	Major Challenges		
Research Theme	**Feedstock Complexity**	**Scale-up Costs**	**Informed Decision Making**
Modeling			**Models** • Predictive analytics for feedstock cost & availability in different areas (LCA/TEA) that can inform whether further investment is warranted in a niche feedstock.
Modularity		**Reactor Design** • Market ready cookie-cutter systems to adapt to regional needs and save time and money on design.	**Data Frameworks** • Data sharing between modular systems for better troubleshooting.
Regionality			**Data Frameworks** • A nationwide marketplace/ platform, which connects players to make use of feedstocks. • An inventory of biomass availability, infrastructure, and economic factors to validate new opportunities.
Starch Reallocation	**Improve Established Processes** • Animal production with complex lignocellulosic feed, but with the same quality as starch feed (for ruminants). • Treatments for non-ruminants (e.g., swine) to use lignocellulosic feed.	**Harness Existing Infrastructure** • The reallocation of corn and its infrastructure in the economy.	**Directed Study** • Defined potential of products from reallocated starch. • Comparison of methane emissions; pretreated lignocellulosic biomass vs. starch. • Economic analysis of pretreated lignocellulosic feed for cattle. **Knowledge sharing** • Engaged farmers that are on board with lignocellulosic feed (via extension agents).

Appendices

Appendix A – Convening Agenda

Day 1 – Tuesday, March 28

8:00 Breakfast

8:30 Welcome & Introductory Remarks
- Genevieve Croft, Schmidt Futures
- Liz McNally, Schmidt Futures
- John Reich, FFAR

8:45 Agenda & Expectations
- Gina Bartlett, Consensus Building Institute

8:55 Introductory Talk on Circular Feedstocks & Bioproduction
- Mary Maxon, Schmidt Futures

9:15 Future Biobased Chemical Industry Landscape
- Bala Subramaniam, University of Kansas

9:35 Panel 1 – Future Feedstocks Challenges & Opportunities
- Nichole Fitzgerald, U.S. DOE Bioenergy Technologies Office, Moderator
- Tristan Brown, SUNY College of Environmental Science & Forestry
- Jeffrey Lacey, Idaho National Laboratory
- Andrew Held, Virent, Inc.

10:20 Small Group Discussion

10:30 Large Group Q&A / Discussion

10:50 Break

11:10 Panel 2 – Transformational Technology Challenges & Opportunities
- Sarah Richardson, MicroByre, Moderator
- Gregg Beckham, National Renewable Energy Laboratory
- William Gong, Origin Materials

Day 1 – Tuesday, March 28

- Erik Hagberg, Archer Daniels Midland (ADM)
- Deepti Tanjore, Lawrence Berkeley National Laboratory

12:00	**Q&A & Discussion**
12:30	**Lunch**
1:30	**Reconvene & Review Plans for the Afternoon**
1:35	**Discussion Workshop – Part 1**
3:30	**Break**
3:45	**Discussion Workshop – Part 2**
4:45 –5:00	**Reflections, Next Steps, Adjourn**
6:00 –7:30	**Reception**

Day 2 – Wednesday, March 29

8:00 **Breakfast**

8:30 **Welcome & Reflections**

- Gina Bartlett, Facilitator Reflections on Day 1
- Group discussion

9:35 **Panel 3 – Future Feedstocks & Opportunities for Biobased Chemicals**

- Katy Christiansen, Lawrence Berkeley National Laboratory, Moderator
- Kevin Barnett, Pyran
- Vineet Rajgarhia, Praj Americas
- Karen Warner, BEAM Circular

10:10 **Large Group Q&A / Discussion**

10:30 **Break**

10:50 **Discussion Workshop – Part 3**

12:00 **Lunch**

12:20 **Wrap-Up & Next Steps**

1:00 **Adjourn**

Appendix B – More About the Convening Organizers

Foundation for Food & Agriculture Research (FFAR): FFAR builds public-private partnerships to fund bold research addressing big food and agriculture challenges. FFAR was established in the 2014 Farm Bill to increase public agriculture research investments, fill knowledge gaps, and complement the U.S. Department of Agriculture's research agenda. FFAR's model matches federal funding from Congress with private funding, delivering a powerful return on taxpayer investment. Through collaboration and partnerships, FFAR advances actionable science benefiting farmers, consumers, and the environment.

Connect: @FoundationFAR

Schmidt Futures: Schmidt Futures is a philanthropic initiative founded by Eric and Wendy Schmidt with a mission to find and connect talented people to solve our world's hardest problems. The BioFutures program aims to catalyze a vibrant, competitive, resilient, and circular U.S. bioeconomy, in which biological resources are transformed sustainably into food, feed, and biomaterials. The BioFutures Program has three key focus areas:
1) repurposing sustainable waste biomass, 2) overcoming engineering constraints, and 3) mobilizing talent for bioeconomy-related federal agencies.

Appendix C – Additional Resources

Participants and organizers noted excellent resources for industry, researchers, and policymakers working in the bioeconomy that are compiled in this section. This list is not comprehensive.

Feedstock Characterization & Availability:

- "Bioenergy Feedstock Library: A biomass repository and research tool that contains information about the chemical, physical, and conversion performance properties of more than 90 crop types and factions from across the United States", Idaho National Laboratory. https://bioenergylibrary.inl.gov/Home/Home.aspx
- "Bioenergy Knowledge Discovery Framework": assessment of the potential economic availability of biomass resources from agricultural lands reported at the farmgate (maps included). https://bioenergykdf.net/farmgate?chapterNumber=4&tabNumber=1

Facilities for Testing & Scale-up of Bioprocessing:

- Advanced Biofuels and Products Process Development Unit, Lawrence Berkeley National Laboratory (LBNL) – https://abpdu.lbl.gov/
- Biomass Feedstock National User Facility, Idaho National Laboratory (INL) – https://bfnuf.inl.gov/SitePages/BFNUF%20Home.aspx
- Argonne National Laboratory Process Development and Scale-Up – https://www.anl.gov/manufacturing/process-development-scaleup-testing
- Michigan State University Bioeconomy Institute – https://bioeconomy.msu.edu/chemical-production-2/
- Integrated Biorefinery Research Facility (IBRF), National Renewable Energy Laboratory (NREL) – https://www.nrel.gov/bioenergy/biochemical-integration-scale-up-piloting.html
- Bioexpression and Fermentation Facility, University of Georgia (UGA) – https://bcmb.franklin.uga.edu/bff/about-bioexpression-and-fermentation-facility
- USDA Forest Products Laboratory – https://www.fpl.fs.usda.gov/
- Laboratory of Renewable Resources Engineering (LORRE), Purdue University – https://engineering.purdue.edu/LORRE_Dev
- Biotechnology Resource Center, University of Minnesota – https://bti.umn.edu/biotechnology-resource-center/

White Papers & Reports:

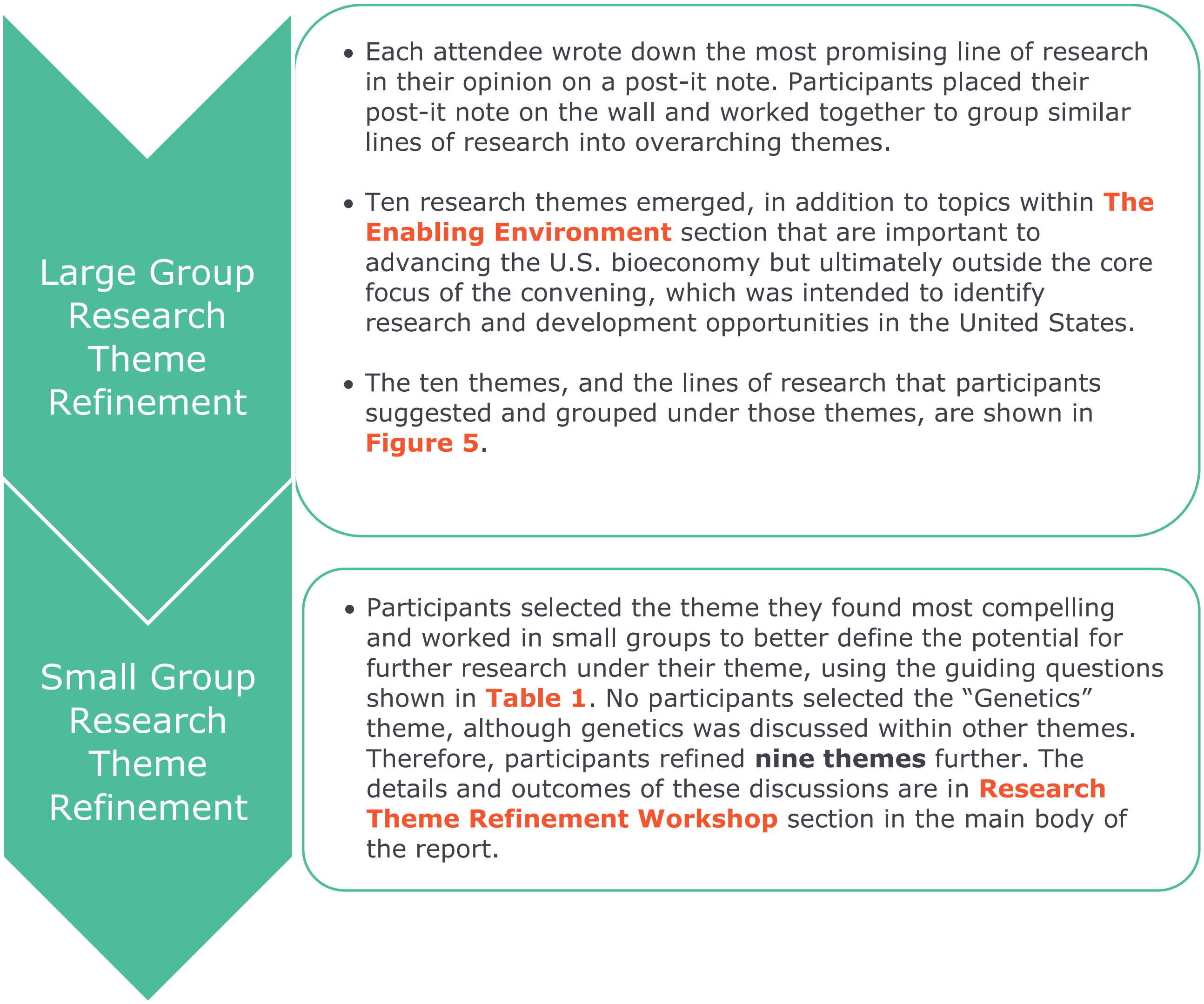
- "The U.S. Bioeconomy: Charting a Course for a Resilient and Competitive Future," April 2022, Schmidt Futures. https://www.schmidtfutures.com/our-work/task-force-on-synthetic-biology-and-the-bioeconomy/
- "Bold Goals for U.S. Biotechnology and Biomanufacturing: Harnessing Research and Development to Further Societal Goals," March 2023, White House Office of Science

and Technology Policy. https://www.whitehouse.gov/wp-content/uploads/2023/03/Bold-Goals-for-U.S.-Biotechnology-and-Biomanufacturing-Harnessing-Research-and-Development-To-Further-Societal-Goals-FINAL.pdf

- “Advancing the Bioeconomy: From Waste to Conversion Ready Feedstocks Workshop Summary Report,” February 2020, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/eere/bioenergy/articles/advancing-bioeconomy-waste-conversion-ready-feedstocks-workshop-summary
- “2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy”, July 2016, U.S. Department of Energy. https://www.energy.gov/eere/bioenergy/articles/2016-billion-ton-report-advancing-domestic-resources-thriving-bioeconomy
- “Top Value-Added Chemicals from Biomass: Volume I: Results of Screening for Potential Candidates from Sugars and Synthesis Gas,” August 2004, U.S. Department of Energy (National Renewable Energy Laboratory and Pacific Northwest National Laboratory). https://www1.eere.energy.gov/bioenergy/pdfs/35523.pdf
- “World Without Waste: A Circular Bioeconomy: A UIDP Bioeconomy Workshop” UIDP, Aug 2021, UIDP. https://uidp.org/custom-type/innovation-in-the-bioeconomy-world-without-waste/
- “New Directions for Chemical Engineering,” 2022, National Academies of Science, Engineering, and Medicine. https://nap.nationalacademies.org/catalog/26342/new-directions-for-chemical-engineering
- “The Importance of Chemical Research to the U.S. Economy,” 2022, National Academies of Science, Engineering, and Medicine. https://nap.nationalacademies.org/catalog/26568/the-importance-of-chemical-research-to-the-us-economy
- “Safeguarding the Bioeconomy,” 2020, National Academies of Sciences, Engineering, and Medicine. https://doi.org/10.17226/25525

Appendix D – Research Theme Refinement Process

Following the feedstocks and technologies discussions, the organizers asked participants to refine research priorities and begin discussing promising lines of inquiry in large-group and small-group discussions, as described below in **Figure 4.**



Large Group Research Theme Refinement

- Each attendee wrote down the most promising line of research in their opinion on a post-it note. Participants placed their post-it note on the wall and worked together to group similar lines of research into overarching themes.
- Ten research themes emerged, in addition to topics within **The Enabling Environment** section that are important to advancing the U.S. bioeconomy but ultimately outside the core focus of the convening, which was intended to identify research and development opportunities in the United States.
- The ten themes, and the lines of research that participants suggested and grouped under those themes, are shown in **Figure 5**.

Small Group Research Theme Refinement

- Participants selected the theme they found most compelling and worked in small groups to better define the potential for further research under their theme, using the guiding questions shown in **Table 1**. No participants selected the "Genetics" theme, although genetics was discussed within other themes. Therefore, participants refined **nine themes** further. The details and outcomes of these discussions are in **Research Theme Refinement Workshop** section in the main body of the report.

Figure 4. Process used during the discussion workshops to refine research themes. The results of this process are covered under Refinement of Feedstock & Technology Priorities.

Biological and Chemical Process Linkages

- Diversity fractionation into lignin & sugars for more feedstocks.
- Renewable chemical processes for end use markets: new renewable chemicals and feedstocks.
- Advanced chemical and biocatalytic technologies for biomass derived feedstocks to value-added products.
- Feedstock decomposition and analysis for native grasses and forbs.
- Identify entry points for biomass derived products in extant commercialized manufacturing processes to speed adoption and investment.
- Recycle existing non-bio infrastructure.
- Develop and process for converting biomass into high quality sugar & lignin.
- Combine bio-catalyst with chemical catalysts.
- Link biology to chemical catalysis
- Alternate organisms and enzymes for the treatment of biomass.
- Big product development – higher margin, lower volume products.
- Use biology for biomass conversion to supplement chemistry.

Genetics

- Genetically modified crops.
- Genetic manipulation for winter crops.

Anaerobic Digestion

- Generate organic acids through arrested organic digestion of food waste (acid phase digestion).
- Encourage and incentivize anaerobic digestion to create methane and volatile fatty acids as a feedstocks.
- Improve the performance of anaerobic digestion.
- Optimize methanogenesis.

Modularity

- Modular pre-processing (as opposed to one-off designs for each plant).
- Demonstration depot with different conversion tech.
- Modular systems standards from pilot to first commercial scale.

Data and Knowledge Sharing

- Develop a data structure framework.
- Credible, accessible data and reports.
- Data availability for characterized biomass, lessons learned.
- Integration of the bioenergy feedstock library.
- A retrospective on previous failures and lessons learned.
- Research to aggregate the best data for feedstock availability, costs, and supply chain risks by region.

Homogeneity

- Partial deconstruction of biomass to make more homogeneous feedstocks.
- Distributed partial deconstruction to make platform chemicals.
- Distributed pre-processing capabilities.
- Systems to homogenize feedstocks to further process.
- Demonstrate the conversion of biomass derived fractions into various products.
- Enabling the use of heterogeneous feedstocks.
- Biomass feedstocks technology for converting basic feedstock chemicals.

Gas Feedstocks:

- Fermentation of gases.
- Using CO2 as a carbon source for product synthesis.
- Produce products from CO2 + H2.
- CO2 capture and reduction.
- New CO2 conversion opportunities created by electrification.
- More discussion on use of CO2.
- Using CO2 as a platform chemical.
- Ways to combine biomass feedstocks and H2 or electron sources.
- Reduce CO2 (fourth generation technology).
- How to test low cost, high efficiency gas fermentation.

Starch Reallocation

- Refocus on starch as a feedstock.
- Optimize starch use by optimizing the use and value of current feedstocks.
- Agree to plan B to redistribute corn as a standard low-cost input for precision fermentation and synthetic biology.

Modeling

- Analytics to predict feedstock cost and availability in different areas.
- Reduce uncertainty via improved systems analysis (LCA/TCA).
- Modeling of the full path of cellulosic economics. From field to product.
- Extending LCA to include water quality and biodiversity.
- AI-based novel pathway design.

Regionality

- Aggregated feedstocks.
- Depots to mobilize, aggregate and format heterogeneous feedstocks.
- Densification/stabilization of feedstocks.
- Lignin valorization of aggregated feedstocks.
- Demonstration for niche resources
- Recycling of existing non-bio infrastructure.
- Regional biomass hotspot tech in situ
- Biomass markets that are regional based.

Figure 5. The results of large group refinement of research priorities. Each attendee proposed what they believed to be the most promising line of research for the circular bioeconomy (represented by each bullet point). Participants worked together to group their proposed lines of research into themes.

Appendix E – Disclaimer

Disclaimer: This document summarizes the views and opinions of those attending the convening and does not necessarily reflect those of the Foundation for Food and Agriculture Research, Schmidt Futures, or other organizations represented during the convening. These organizations do not make any warranty, expressed or implied, or assume any liability or responsibility for the accuracy, completeness, or usefulness of any information disclosed in the report. Any specific commercial product, trademark, or manufacturer referenced herein is shared for information purposes only and does not constitute an endorsement or recommendation of the product by the authors or the respective organizations they work for.

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