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INTEGRATING CO_2 INTO BIOMANUFACTURING

WORKSHOP REPORT

Lawrence Berkeley National Laboratory (Berkeley Lab) | 2021

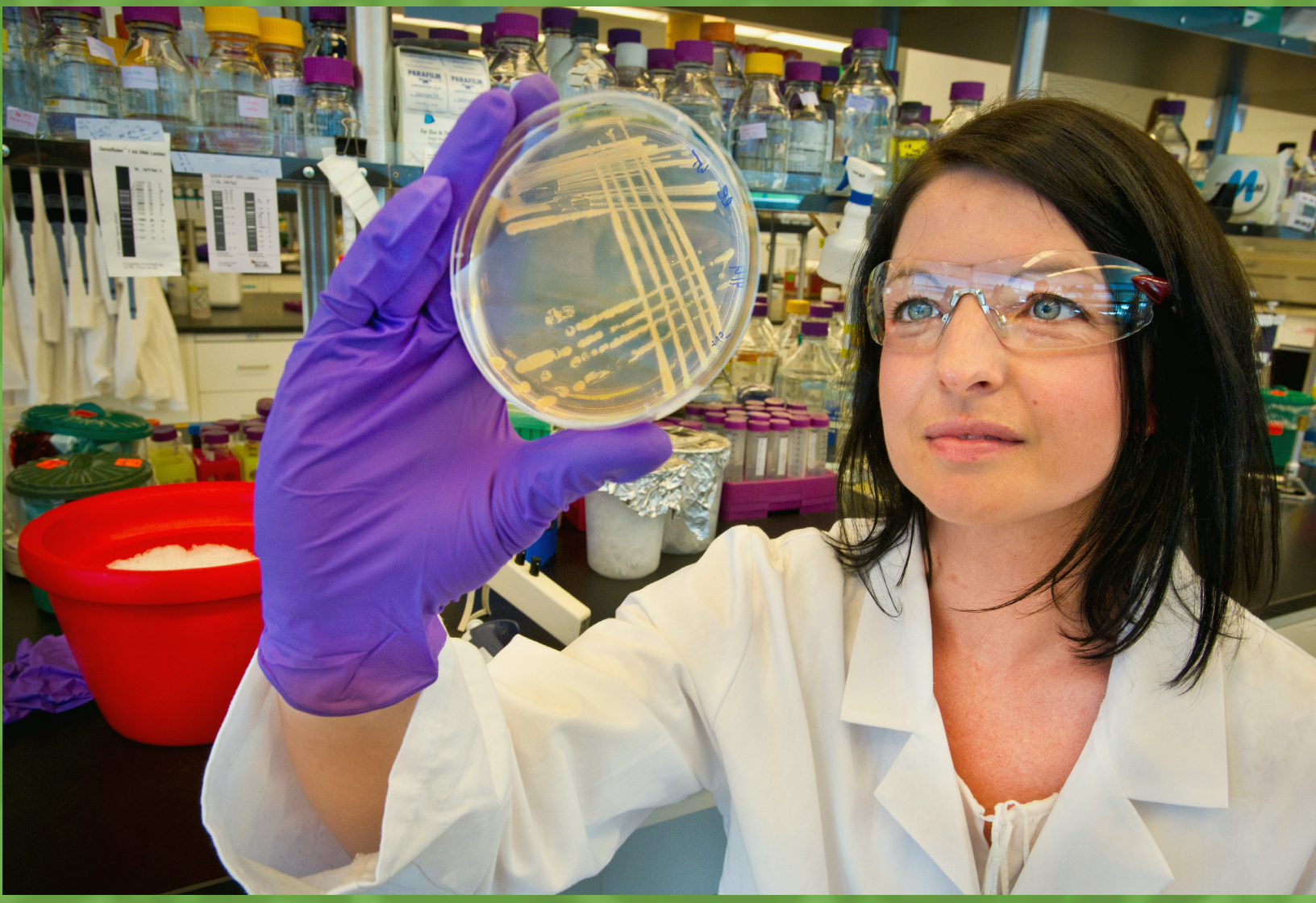

TABLE OF CONTENTS

Executive Summary 2

About the Workshop 3

Introduction 4

Workshop Insights 5

Science Drivers and Research Opportunities 5

CO_2 Uptake 5

CO_2 Fixation 6

Products from CO_2 7

Hybrid Electrochemical and Biological Approaches 8

Summary: Research Opportunities 9

CO_2 Uptake 9

CO_2 Fixation 9

Products from CO_2 9

Hybrid Electrochemical and Biological Approaches 9

Appendix 1: Berkeley Lab Facilities and Programs Relevant to CO_2 Biomanufacturing 10

Appendix 2: Workshop Participants 11

Appendix 3: Workshop Agenda 12

EXECUTIVE SUMMARY

Mitigating climate change stemming from human activities that emit greenhouses gases, primarily carbon dioxide (CO_2), is a central global challenge. Reducing current CO_2 emissions as well as removing CO_2 from the air is critical to prevent global warming from increasing beyond 2°C. Much of the research and development on mitigating CO_2 emissions at their point of origin have been focused on capturing and sequestering CO_2. However, CO_2 mitigation is also an opportunity to incorporate CO_2 into the bioeconomy through sustainable biomanufacture of biofuels, biochemicals and long-lived bioproducts. Biological systems are uniquely capable of capturing and converting CO_2, so incorporating CO_2 as a feedstock into the biomanufacturing enterprise provides a promising opportunity to establish a new sector in the US bioeconomy that directly mitigates climate change. CO_2 biomanufacturing, which encompasses biological CO_2 conversion as well as conversion of reduced products derived from CO_2, including: carbon monoxide (CO), formate, and methanol can leverage both plants and microbes for bioproduction. Therefore it is valuable to consider both plants and microbes together in developing a research agenda for biomanufacturing, because they have related CO_2 uptake mechanisms and CO_2 fixation pathways. Biodesign principles, systems biology techniques and heterologous production pathways for plants and microbes that have been developed for the conversion of plant biomass can be reimagined to improve the ability of plants and microbes to use CO_2 more efficiently and produce biofuels, bioproducts and biomaterials.

On November 24, 2020, Lawrence Berkeley National Laboratory (Berkeley Lab) hosted a virtual workshop on biomanufacturing using CO_2 to identify ways to integrate the study of biological CO_2 conversion in plants and microbes. The workshop participants were asked to evaluate current gaps and challenges in biological CO_2 conversion, focusing on three main areas: CO_2 uptake, CO_2 fixation, and bioproducts that can be obtained from CO_2. For CO_2 uptake, capture of atmospheric CO_2 was identified as a unique property of biological systems. Opportunities to deploy carbon concentrating mechanisms (CCMs) in biomanufacturing and discovery of new CCMs that may be present in soil chemoautotrophic microbes were discussed. The possibility to improve plant biomass yields through engineering CO_2 uptake was identified as a compelling research challenge. Participants discussed improvements in current CO_2 fixation pathways like the Calvin-Benson-Bassham (CBB) cycle, exploiting alternative CO_2 fixation pathways found in microbes, and designing *de novo* pathways. The identification of microbial hosts to exploit these alternative and synthetic pathways was identified as a promising research direction. Products from CO_2 were divided into two categories: carbon-neutral, for biofuels and commodity chemicals, and carbon-negative, for biomaterials that can be engineered to sequester carbon for long time scales, either in the terrestrial biosphere or in the built environment. For hybrid bio-electrochemical systems, further understanding of C1 microbial metabolism and integration of electrodes and microbes in single bioreactors by harmonizing rates and minimizing toxic by-products, were discussed.

ABOUT THE WORKSHOP

On November 24, 2020, Lawrence Berkeley National Laboratory (Berkeley Lab) hosted a virtual workshop on Integrating CO_2 into Biomanufacturing to identify ways to integrate the study of biological CO_2 conversion in plants and microbes with the purpose of developing systems that can generate biofuels, bioproducts and biomaterials that can mitigate climate change. The workshop leverages Laboratory-Directed Research and Development investments in biological CO_2 conversion and work on biosystem design of plants and microbes performed in the Joint BioEnergy Institute and Joint Genome Institute. The workshop also leverages work performed at the Joint Center for Artificial Photosynthesis (JCAP) and Liquid Sunlight Alliance (LiSA) on photo-electrochemical water-splitting and CO_2 reduction. This workshop brought together researchers from the units in the Biosciences Area at Berkeley Lab (Biological Systems and Engineering, Environmental Genomics and Systems Biology, Molecular Biophysics and Integrated Bioimaging and Joint Genome Institute) Berkeley Lab's Chemical Sciences Division in the Energy Sciences Area and the Energy Technologies Area. This workshop is an initial effort to establish research directions for integrating CO_2 into biomanufacturing focused on CO_2 bioconversion and we look forward to engaging with other national laboratories, academic partners, and private industry to advance this critical area.

The workshop focused on science drivers and research areas for integrating CO_2 into biomanufacturing, dividing the topic into: CO_2 uptake, CO_2 fixation, products from CO_2, and hybrid approaches (electrochemical-biological) to CO_2 conversion. The workshop was framed by overview talks from Biosciences Area leadership and researchers involved in biological CO_2 fixation. These talks were followed by three breakout sessions that asked participants to identify gaps in CO_2 conversion, possible research directions and articulate what success looks like in the short, near and long-term.

24 attendees took part in the workshop and the outputs of the workshop will be **1)** a workshop report describing the participants' discussions, **2)** a position paper providing perspective on biological CO_2 conversion and, **3)** concepts for new research programs.

This workshop was funded with internal Biosciences Strategic Programs Development funds.

INTRODUCTION

Anthropogenic climate change is a global issue of enormous magnitude that threatens human civilization. Carbon dioxide (CO_2) generated from human activities, primarily the combustion of fossil fuels, energy-intensive agriculture, and construction, is the most important contributor to climate change. Reducing current CO_2 emissions as well as removing CO_2 from the air is critical to prevent global warming from increasing beyond 2°C. There has been substantial recent interest in developing technologies to capture CO_2 from point sources, such as ethanol production facilities and power plants, and from atmospheric CO_2. Some of these technologies will be deployed to capture CO_2 and sequester it by storage in geologic formations, others capture CO_2 and use the captured CO_2 for chemical synthesis. However, current conversion technologies are inadequate to capture and convert CO_2 from point sources and the air efficiently or economically.

An alternative way to think about the problem of CO_2 mitigation is as an opportunity to incorporate CO_2 into sustainable biomanufacturing. Since transportation fuels and commodity chemicals are multi-carbon compounds, there are large global markets for products that can be made from CO_2. Biological systems are uniquely capable of capturing and converting CO_2, so incorporating CO_2 into biomanufacturing provides a promising opportunity to establish a new sector in the US bioeconomy that directly mitigates climate change. The introduction of CO_2 into biomanufacturing complements biomanufacturing strategies that have been established based on starch and lignocellulosic-derived sugars.

CO_2 biomanufacturing can leverage both plants and microbes for bioproduction. Plants require CO_2 to grow and therefore bioproducts in plants naturally are synthesized from CO_2. Therefore, biodesign improvements to CO_2 uptake and fixation linked to targeted manipulation of metabolic pathways will yield bioproducts that can be extracted or incorporated into soil upon plant senescence. These bioproducts may be carbon neutral if used as fuels or commodity chemicals or carbon negative if sequestered in long-lived materials or soils. Microbes, including bacteria, archaea and microalgae, have a variety of different strategies to fix CO_2, including photosynthetic and chemoautotrophic (non-photosynthetic) CO_2 fixation. This variety in host and mechanism will lead to flexible strategies for biomanufacturing that can be adapted to different conditions and process configurations. It is valuable to consider both plants and microbes together in developing a research agenda for CO_2 biomanufacturing, because they have related CO_2 uptake mechanisms, CO_2 fixation pathways and can be engineered with the same heterologous pathways for biomanufacturing.

The rapid reduction and expanding deployment of renewable electricity provides a potential pathway to use electrons to generate reductants for microbial CO_2 conversion. Currently, the most attractive option is to convert electricity to hydrogen gas (H_2), which can serve as a reductant for both aerobic and anaerobic chemoautotrophs. However, H_2 is poorly soluble in aqueous solution, therefore CO, formate, and methanol may be alternative substrates to H_2 or CO_2 for microbial conversion that are freely soluble in aqueous solution.

Biodesign principles, systems biology techniques and heterologous production pathways for plants and microbes that have been developed to improve the conversion of biomass through sugar and aromatic intermediates can be reimagined to improve the ability of plants and microbes to use CO_2 more efficiently and produce biofuels, bioproducts and biomaterials.

WORKSHOP INSIGHTS

The workshop participants were asked to evaluate current gaps and challenges in biological CO_2 conversion, focusing on three main areas: CO_2 uptake, CO_2 fixation, and bioproducts that can be obtained from CO_2. The participants included both microbial and plant biologists, so approaches to improving CO_2 conversion and possible synergies between these two platforms were explored. The participants also considered hybrid approaches that combined electrochemical, photo-electrochemical, and biological conversion through C1 intermediates: carbon monoxide (CO), formate, and methanol.

Science Drivers and Research Opportunities

CO_2 Uptake

Air Capture of CO_2: Capturing and concentrating CO_2 from the atmosphere is essential for removing CO_2 from air. Chemical methods are being developed to perform air capture of CO_2; however, achieving efficient and cost-effective CO_2 air capture remains a significant challenge. A variety of plants and microbes can grow by concentrating CO_2 for autotrophic growth. Understanding these carbon concentrating mechanisms (CCMs), along with approaches to improve their efficiency, will enable improved biological CO_2 air capture that can be applied to draw down CO_2 from the atmosphere and integrate into biomanufacturing.

Photosynthetic microbes, including cyanobacteria and algae, have developed carbon concentrating mechanisms to deliver low concentrations of CO_2 from air using microcompartments, referred to as carboxysomes (cyanobacteria) and pyrenoids (algae), to concentrate CO_2 in close physical proximity to the key CO_2-fixing enzyme ribulose biphosphate carboxylase (Rubisco). This CCM mechanism is also found in some chemolithoautotrophic bacteria. Certain land plants have developed CCM mechanisms, the C4 pathway (tropical grasses) and the Crassulacean acid metabolism (arid plants), that are distinct from the microbial systems and involve malate as carrier of CO_2 to Rubisco. A key fundamental science gap in understanding CCM mechanisms is to discover whether there are additional CCM mechanisms that may be employed by plants and microbes. In support of this hypothesis, microbes that have alternative CO_2 fixation pathways lack known CCMs, though many of them are capable of growing autotrophically in air. A key engineering gap is that the principles for constructing CCMs are not known.

CO_2 Capture from Point Sources: CO_2 from point sources, such as ethanol production (90–99% [CO_2]), refinery offgas (50% [CO_2]) concrete production, and power plant effluent (3–14% [CO_2]), are both substantial sources of CO_2 emission and opportunities to co-locate facilities for biological CO_2 conversion. An important knowledge gap is to understand the effect of contaminants in these gas streams on biological CO_2 conversion and how inhibitors in these gas mixtures can be overcome.

Research opportunities: Designing strategies for introduction of CCMs into plants and microbes has the potential to improve CO_2 uptake and conversion, leading to advances in plant biomass productivity and biotechnological applications that can convert gas streams with low concentrations of CO_2. This design strategy will require understanding how the components of

traditional CCMs (based on carboxysomes and pyrenoids) function to concentrate CO_2 and whether these functional elements can be transferred to plants and microbes that do not have these capabilities. The compartments that house the components of the CCMs may be repurposed to combine catalysis with sequenctial separation for reactions beyond Rubisco-based CO_2 fixation. This membrane can be used to confine CO_2 (e.g. separation) with other CO_2- fixing catalysts (synthetic or natural) that do not suffer from the shortcomings of Rubisco. Discovery of new, non-carboxysome-based CCMs in microbes may identify complementary functional elements that can also be introduced into plants and microbes. Soils may harbor a large reservoir of these CCMs as soil autotrophs need to respond to widely fluctuating concentrations of CO_2. These non-carboxysome-based CCMs also may be important in improving CO_2 conversion in microbes with alternative or synthetic CO_2 fixation pathways. An important step in the research area is to identify model systems that are sources of CCMs and target hosts to develop engineering principles for installation of these CCMs. These hosts could include crops and associated model plants (e.g. *Arabidopsis thaliana* and poplar) and chemoautotrophic bacteria that have been demonstrated to produce biofuels and bioproducts from CO_2.

CO_2 Fixation

Calvin-Besson-Bassham (CBB) Cycle and Rubisco: All plants and the vast majority of microbes use the CBB cycle to fix CO_2 into biomass. The central enzyme in this cycle, ribulose biphosphate carboxylase, Rubisco, is a slow enzyme that functions as an oxygenase as well as a carboxylase. In addition, the CBB cycle is requires high levels of NAD(P)H and ATP to function. To mitigate the oxygenase bypass of Rubisco, plants and microbes have developed photorespiration pathways to recycle the products of Rubisco oxygenase activity. The carboxysome-based CCMs described above are also adaptations to the poor activity of Rubisco, concentrating CO_2 in the vicinity of the enzyme to enhance kinetics. While the CBB cycle is ubiquitous, its poor efficiency remains a significant challenge in deploying CO_2 biomanufacturing in plants and microbes.

Alternative CO_2 fixation pathways: Bacteria and archaea have developed alternative CO_2 fixation pathways, some which are less energy intensive than the CBB pathway and use carboxylases that have higher rates and lower oxygen sensitivity compared to Rubisco. However, these alternative pathways are often present in slow-growing microbes that are difficult to genetically manipulate, limiting our understanding of these alternative pathways and complicating the implementation of these pathways in more tractable hosts. An additional complication is that the most energy efficient fixation pathways, the Wood-Ljungdahl pathway and the reverse TCA cycle, have Fe-S proteins with pronounced oxygen sensitivity as part of each pathway.

Synthetic pathways: The drawbacks associated with the CBB pathway and the alternative CO_2 fixation pathways have led to proposals for synthetic pathways that combine features of CO_2 fixation pathways that minimize energy expenditure and maximize CO_2 fixation rates. These pathways have been demonstrated *in vitro* but have not been achieved *in vivo.*

Research opportunities: There are multiple approaches to redesign CO_2 fixation to generate plants and microbes that convert CO_2 more rapidly and more efficiently than native systems. Large research efforts have focused on improving the kinetics of Rubisco and eliminating its oxygenase activity. However, comparatively less work has been done on improving the overall CBB cycle by diverting intermediates in the pathway through reactions that consume less ATP and NAD(P)H, which will improve the efficiency of CO_2 conversion. This improvement will increase biomass yield in plants and lower the amount of reductant needed for microbial transformation of CO_2. A related approach integrates alternative CO_2 fixation pathways into existing autotrophs that use the CBB cycle. These alternative pathways can take advantage of intermediates generated in the CBB cycle or in central

metabolism. An excellent example of this approach has been demonstrated in cyanobacteria, where a novel pathway, the malyl-glycerate cycle, integrates CO_2 carboxylation reactions from central metabolism into a CO_2 fixation pathway that complements the native CBB cycle.

For microbes, potential hosts that have alternative CO_2 fixation pathways may be domesticated by uncovering conditions for successful transformation and genetic manipulation. These new hosts can serve as alternative to current microbial hosts for CO_2 conversion, which predominantly use the CBB cycle. These alternative CO_2 fixation pathways can also be expressed in a model host such as *E. coli,* which would allow production of a varied suite of biofuels and bioproducts from CO_2. In both cases, substantial research would need to be conducted to develop these hosts with alternative CO_2 fixation pathways for application in biomanufacturing. It is possible that entirely synthetic biological CO_2 fixation pathways can be demonstrated *in vitro,* then transferred to an *in vivo* model systems; however, implementation of this approach will require extensive remodeling of native metabolism and finely tuned heterologous protein expression.

For all of these approaches described in the CO_2 fixation section, the biosystem design approaches will require complementary systems biology studies, 13C isotopic tracing and metabolic modeling to identify potential bottlenecks when existing CO_2 fixation pathways will be altered or when new pathways will be introduced. A combination of experiment and modeling will be crucial to successfully improving biological CO_2 fixation.

Products from CO_2

Heterologous pathways and hosts: A wide array of biofuels and bioproducts have been produced in microbes from biomass-derived sugars. In principle, these products can also be directly from CO_2; however, methods to express the heterologous proteins in these pathways in plants and CO_2-converting microbes are not well-established. Controlled expression of heterologous proteins is critical to achieve production titers relevant to biomanufacturing. Host selection for products will also depend on native metabolisms as well as the ability of the host to be integrated into a biomanufacturing process.

Biofuels and commodity chemicals: The largest markets for CO_2-based products are in biofuels and commodity chemicals. Generating these products by combining light or renewably-derived reductants and CO_2 using engineered microbes is a promising method for carbon neutral biomanufacturing that does not require agricultural production. Significant improvements in titer, rate and yield are required to establish this pathway for biofuels and bioproducts. Also, strategies where intermediates are produced biologically from CO_2 (ethanol, isobutanol) and then converted to final products by catalysis need to be considered alongside complete biological conversion.

Long lived materials: An attractive goal for biomanufacturing is to generate bio-based materials that are capable of long-term carbon sequestration. Plants can be engineered to produce recalcitrant carbon compounds (lignin, suberin) in soils, directly sequestering CO_2 fixed through photosynthesis. Microbes can be engineered to produce precursors for polymers that can be incorporated into building materials. Examples of these polymers include carbon fiber, which can be produced from bio-based 3-hydroxypropionate, and polyurethanes, which can be produced from bio-based polyols. Both of these polymers can be used as building materials, which will facilitate long-term storage of carbon derived from CO_2.

Research opportunities: A critical decision in biomanufacturing with CO_2 is to determine whether the bioproduct is more efficiently and cost-effectively produced in plants or in microbes. This determination will involve techno-economic analysis (TEA) of the proposed process as well as life cycle assessment (LCA) to identify the process with lowest emissions.

Conversion of CO_2 to products is an inherent property of plants as CO_2 is their only substrate. Therefore, the ability to divert intermediates in CO_2 fixation and reengineer central metabolic pathways are essential for developing strategies to generate bioproducts from CO_2. Initial plant bioproduct research will likely need to be conducted in model plants with relatively short generation times such as *Arabidopsis* or *Brachypodium* to accelerate discovery. However, these CO_2 conversion technologies will ultimately need to be deployed in crops to enable bioproduction at scale. Therefore, the choice of bioproduct and plant will be influenced by agronomic considerations. TEA/LCA will guide whether bioproducts will be molecules that may be stored in the soil or will be harvested for applications in biomanufacturing. Bioproducts introduced into soil will need to be tested to measure their persistence and to determine any adverse environmental impacts. Plant bioproducts for biomanufacturing can be accumulated in specific plant tissue from which they can be easily extracted. Successful bioproduct generation from CO_2 in plants will require advances in plant biosystems design, including engineering of plant metabolic pathways and synthetic biology tools for localizing bioproducts in plant tissues.

For microbes, a number of factors need to be considered for CO_2 bioproduction, based on the requirements of substrate availability (light, electricity, H_2), cost and scale. These considerations will dictate whether a photosynthetic microbe or non-photosynthetic microbe is chosen for bioproduction. If a non-photosynthetic system is chosen, the decision to choose an anaerobic host or aerobic host also needs to be made. Anaerobic autotrophs convert CO_2 with high efficiencies; however they have limited product ranges (2–4 carbon chains) and are difficult to engineer. Aerobic autotrophs can produce a wider variety of products (2–18 carbon chains) and are more straight-forward to engineer, but are less efficient at converting CO_2, requiring reductant consumption for ATP generation.

Hybrid Electrochemical and Biological Approaches

Microbial C1 metabolism: Microbes possess metabolic pathways for conversion of the products of CO_2 reduction: CO, formate, and methanol. These C1 intermediates are an alternative to direct biological CO_2 conversion, and have the advantage of being highly soluble in aqueous solution, which obviates the need for CCMs. Conversion of these intermediates has recently been scaled for biomanufacturing: Lanzatech has commercialized the anaerobic conversion of CO to ethanol from steel mill off-gas and ICI commercialized the conversion of methanol, obtained from natural gas, to single cell protein. Therefore, these C1 intermediates may be more viable for biomanufacturing in the near term than direct bioconversion of CO_2. Pathways for conversion of these C1 intermediates have been expressed in model organisms (*E. coli, S. cerevisiae*); however these heterologous systems perform poorly compared to native hosts, suggesting that further systems biology studies of these hosts are needed to make the C1 pathways broadly viable for production.

Bioelectrochemical reactors: The C1 intermediates can be produced by electrochemical reduction of CO_2 using renewable sources of electricity (photovoltaics, wind, hydroelectric). An intriguing variation on biological CO_2 is a hybrid approach where CO_2 is converted electrochemically to C1 intermediates in the same bioreactor that the biological conversion occurs. This process configuration combines advantages of both the chemical and biological systems but requires alignment in scales and rates to be deployed successfully.

Research opportunities: Fundamental understanding of the conversion of C1 intermediates derived from CO_2 (CO, formate, and methanol) is still not sufficient to reconstitute these metabolic pathways in model hosts at rates and biomass yields that are comparable to native systems, suggesting that further systems biology investigations of microbes that convert these C1 compounds will provide new insights into their metabolism. These three intermediates are also toxic to microbes, so identifying mechanisms to alleviate this toxicity is also necessary. There are opportunities, especially with CO and formate, to directly integrate electrochemical and biological conversion in one bioreactor. These hybrid bioreactors will require the rates of electrochemical and biological conversion to be harmonized and any toxic effects from electrochemistry on the biological system mitigated.

Summary: Research Opportunities

CO_2 Uptake

- Understand how components of traditional CCMs function to concentrate CO_2 to transfer to plants and microbes and build compartments based on these components for other microbial conversion.
- Discover new, non-carboxysome-based CCMs in microbes that may have complementary functional elements that can also be introduced into plants and microbes.
- Identify model systems that are sources of CCMs and target hosts to develop engineering principles for installation of these CCMs.

CO_2 Fixation

- Improve the efficiency of the overall CBB cycle by diverting intermediates in the pathway through reactions that consume less ATP and NAD(P)H.
- Integrate alternative CO_2 fixation pathways into existing autotrophs to take advantage of intermediates generated in the CBB cycle or in central metabolism.
- Domesticate hosts that have alternative CO_2 fixation pathways and/or express these alternative pathways in a model host such as *E. coli.*

Products from CO_2

- Develop TEA/LCA-based decision tree to determine whether a bioproduct is more efficiently and cost-effectively produced in plants or in microbes from CO_2.
- Divert intermediates in CO_2 fixation and reengineer central metabolic pathways to generate bioproducts from CO_2 in plants.
- Establish whether a microbially produced bioproduct is generated under photosynthetic or chemosynthetic conditions and whether it should be produced in aerobic or anaerobic chemoautotrophs.

Hybrid Electrochemical and Biological Approaches

- Further systems biology investigations of microbes that convert these C1 compounds (CO, formate, and methanol) will provide new insights into their metabolism.
- Integration of electrochemical and biological conversion in one bioreactor.

APPENDIX 1: BERKELEY LAB FACILITIES AND PROGRAMS RELEVANT TO CO_2 BIOMANUFACTURING

The **Joint Genome Institute** (JGI) performs large-scale sequencing of DNA and RNA and computational genomic analyses, and will support both biosystems design and systems biology effort for CO_2 biomanufacturing. Discovery of new CCMs and new CO_2 fixation pathways will rely on JGI tools.

The Advanced Biofuels and Bioproducts Development Unit (ABPDU) is a bioprocess scale-up facility that enables early stage innovation by performing process science to transfer fermentation and downstream purification technologies from microtiter plates to bioreactors at 100s of liters. The ABPDU currently has small scale facilities for gas fermentation that can be scaled to support CO_2 biomanufacturing.

The Agile BioFoundry (ABF) integrates industrially relevant production microbes, advanced tools for biological engineering and data analysis, and robust, scaled-up processes for integrated biomanufacturing. The ABF has collaborative projects on CO_2 biomanufacturing with private companies and the tools developed by the ABF will be adapted for CO_2 biomanufacturing.

The **Joint BioEnergy Institute** (JBEI) is a U.S. Department of Energy Bioenergy Research Center dedicated to developing advanced biofuels — liquid fuels derived from the solar energy stored in plant biomass that can replace gasoline, diesel and jet fuels. Researchers are using the latest tools in molecular biology, chemical engineering, computational and robotic technologies to transform biomass into biofuels and bioproducts. JBEI has developed high-throughput microfluidic systems that can be used for large-scale screening of samples to help develop diagnostic probes.

The **Liquid Sunlight Alliance** (LiSA) will establish the science principles by which durable coupled microenvironments can be co-designed to efficiently and selectively generate liquid fuels from sunlight, water, carbon dioxide, and nitrogen. Founded in 2020, LiSA is one of two projects in the Fuels from Sunlight Energy Innovation Hub funded by the U.S. Department of Energy, Office of Science, Basic Energy Sciences.

APPENDIX 2: WORKSHOP PARTICIPANTS

Steven Singer, Senior Scientist, Biological Systems and Engineering Division

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Millicent Firestone, Deputy Program Manager for the Office of National & Homeland Security

APPENDIX 3: WORKSHOP AGENDA

Integrating CO_2 into Biomanufacturing
November 24, 2020
1:00–4:30 pm
Zoom/Miro

Topic	Speaker	Time
Purpose of the workshop/Vision for CO_2 Biomanufacturing	**Steve Singer**	1:00–1:10 pm (10 minutes)
How CO_2 biomanufacturing aligns with U.S. and global bioeconomy strategies	**Mary Maxon**	1:10–1:20 pm (10 minutes)
History of the CARBON Big Idea	**Blake Simmons**	1:20–1:25 pm (5 minutes)
Engineering photosynthesis	**Patrick Shih**	1:25–1:32 pm (7 minutes)
Engineering plants for CO_2 capture	**Aymerick Eudes**	1:32–1:39 pm (7 minutes)
CO_2 biomanufacturing LDRD	**Eric Sundstrom**	1:39–1:46 pm (7 minutes)
BREAK		1:46–1:56 pm (10 minutes)
Sustainable CO_2 biomanufacturing TEA/LCA	**Corinne Scown**	1:56–2:06 pm (10 minutes)
Introduction to Miro and practice exercise	**Katy Christiansen**	2:06–2:21 pm (15 minutes)
Discussion 1: Maximizing capture and use of CO_2 by plants and microbes		2:21–3:06 pm (45 minutes)
BREAK		3:06–3:16 pm (10 minutes)
Discussion 2: Maximizing efficiency of CO_2 transformation into products		3:16–4:01 pm (45 minutes)
STRETCH		4:01–4:05 pm (4 minutes)
Discussion 3: Beyond biology: integration of biology and electrochemistry		4:05–4:25 pm (20 minutes)
Wrap up and next steps		4:25–4:30 pm (5 minutes)

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