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OPPORTUNITIES & CHALLENGES IN BIOINDUSTRIAL MANUFACTURING:

An Environmental Scan of Workforce Development in the Industry

Authors

Cindy Ziker, *Ph.D., M.P.H.*
Jessica Johnson, *M.S.*
Paul Paredes

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Reviewed by

Dr. Karen McDonald, *Distinguished Professor, Chemical Engineering*
University of California, Davis

Dr. Corin Slown, *Associate Professor, Science Education*
California State University Monterey Bay

Angela Cosani, *Co-founder and CEO* of Bioscience Core Skills Institute

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STEMconnector is a professional services firm committed to increasing the number of STEM-ready (Science Technology Engineering Math) workers in the global talent pool. We engage stakeholders across the corporate, postsecondary, nonprofit, government, and K-12 sectors to enable optimal outcomes for historically underrepresented and underserved individuals. Our Research Team focuses on complex problems and research-based solutions designed to improve the STEM workforce. We work with STEM innovators and thought leaders across sectors to inform, inspire, and connect organizations with a passion for and vested interest in re-envisioning and growing a STEM-ready workforce. Visit https://stemconnector.com to learn more.

Table of Contents

Introduction

The need to advance the bioindustrial manufacturing workforce in order to meet the challenges of sustainability and national security will require new strategies in preparation, technology innovation, and collaboration across sectors. Bioindustrial manufacturing is a portion of the overall US bioeconomy, defined by the authors of "Safeguarding the Bioeconomy" as biologically-based chemicals, fuels, plastics, materials, consumer products, and foodstuffs.[1] It uses biology to make industrial products that can reduce pollution and address global issues like climate change by creating new materials or sustainable alternatives to existing petroleum-based materials, thus producing materials with physical and chemical properties that are not currently available.

This environmental scan of the bioindustrial manufacturing industry is funded by the Bioindustrial Manufacturing And Design Ecosystem (BioMADE), a public-private partnership that is the eighth Department of Defense (DoD)-sponsored Manufacturing Innovation Institute (MII) and the 16th institute in the Manufacturing USA network.[2] BioMADE's goal is to enable domestic bioindustrial manufacturing at all scales, develop technologies to enhance U.S. bioindustrial competitiveness, de-risk investment in relevant infrastructure, and expand the biomanufacturing workforce to realize the economic promise of industrial biotechnology.[3] To learn more about BioMADE visit https://www.biomade.org/about-biomade.

This effort examines the current factors that are impacting the advancement of a resilient bioeconomy and a prepared workforce for the future. It was designed to investigate current gaps and potential undiscovered assets that can contribute to improving the bioindustrial manufacturing workforce and increase understanding about the political, economic, sociocultural, technological, environmental, and legal factors that impact the industry. Potential opportunities, threats, trends, risks, and challenges that exist in meeting industry demands were also identified. Findings from this study are intended to inform efforts to build a diverse and resilient bioindustrial manufacturing workforce. It is not intended to be an exhaustive review of every influence on the bioindustrial manufacturing ecosystem, but rather a scan of some of the key factors that are impacting the current landscape of the workforce.

Methodology

Methods used to accomplish this scan included the use of the PESTEL Analysis Framework, which is a six-point framework grounded in the pioneering work by Francis J. Aguilar of the Harvard Business School and described in his book “Scanning the Business Environment.”[4]

The framework was used to structure an examination of the political, economic, sociocultural, technological, legal, and environmental (PESTEL) factors that have an impact on the current and expected future state of the bioindustrial manufacturing industry.[5]

Research questions that guided the scanning of the bioindustrial manufacturing ecosystem include:

- What opportunities, challenges, trends, and threats currently exist in the bioindustrial manufacturing ecosystem?
- What are the gaps in the bioindustrial manufacturing workforce?
- What are some recommendations for enhancing the bioindustrial manufacturing industry?

This report outlines the findings revealed as an outcome of these efforts.

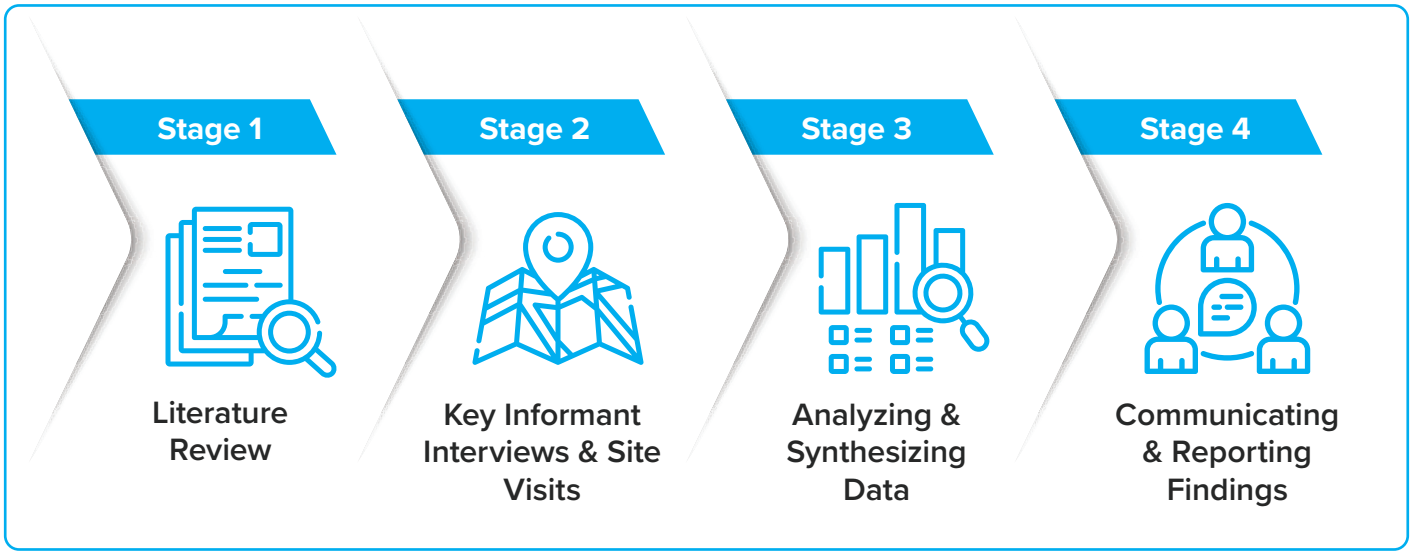
Figure 1: PESTEL factors addressed in the PESTEL analysis.

The environmental scan was conducted using a four-stage process. **Stage 1** involved conducting a literature review that included over 400 citations. During **Stage 2**, STEMconnector researchers conducted over 41 semi-structured interviews. Key informants that participated in interviews included BioMADE and STEMconnector members and represented a wide-range of expertise from academia, industry, and non-profit organizations. Interviewees were also asked to provide recommendations for addressing identified challenges and to provide insights on best practices for developing a diverse and well-prepared workforce.

Stage 3 focused on collecting and documenting insights during seminal meetings and site visits with relevant stakeholders. This included presentations and table discussions that were documented during STEMconnector's Innovation Lab, held at the College of San Mateo in San Bruno California on July 21, 2022,[6] as well as during the BioMADE Annual Meeting, held in St. Paul Minnesota on June 13-15, 2022, and the NSF Capacity Building Summit, held at Skyline College in Burlingame, California on June, 27-29, 2022. Attendees at these events included representatives from academia, industry, non-profit agencies, the Department of Defense, and BioMADE.

During **Stage 4**, transcripts from interviews and table discussions were coded using inductive qualitative coding methods and QDA Minor Lite software. Findings from the literature review, interviews, site visits, convenings, and meeting presentations were analyzed by conducting a PESTEL Analysis.

Figure 2: Four Stage Process for conducting the environmental scan.



Political Factors

Impacting the Bioindustrial Manufacturing Industry

Summary

The political arena plays a significant role in the advancement of national security and the bioeconomy in the United States. Recent political breakthroughs, such as the Inflation Reduction Act[7] and the CHIPS and Science Act of 2022 may change the future of the bioindustrial manufacturing industry. On September 12, 2022, President Biden signed the Executive Order on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy. Workforce development in bioindustrial manufacturing is influenced by these political decisions, and others that impact financial investments in scientific research, environmental initiatives, health care reform, and technological innovations. Political factors that present opportunities for growth in these areas include legislation, global campaigns, and policies. Challenges include delays in the enactment of policies and provisions for improving the bioeconomy, competing initiatives, a lack of public understanding of the issues impacting the workforce, and bipartisan support for investments needed to accelerate the industry. Threats, such as the conflict in Ukraine that increase instability of supply chains and immigration restrictions, can potentially limit access to talent that can spur innovation in the field.

Opportunities

- Inflation Reduction Act 2022
- Active local government affairs committees that advocate for policies that promote bioindustrial manufacturing
- State government funding policies that support investments in start up initiatives
- Federal government funding through the National Science Foundation and other government agencies

Challenges

- Political barriers that delay the approval of funding resources
- Lack of awareness of the need to support policies that promote the bioeconomy
- Lack of awareness of initiatives that can improve the bioeconomy

Threats

- Ukraine war and national security
- Cybersecurity risks
- COVID-19 in the context of supply chain issues
- Competing policy initiatives that support invesments in other areas

Trends

- Support for green jobs
- Increased awareness of the need for government agencies to work collaboratively with industry
- Positive attitudes toward actions for mitigating climate change

Opportunities

Increased awareness of the consequences of climate change has led to an influx in political efforts to address climate resilience. Since rejoining the Paris Agreement in January of 2021, America's commitment to threats from climate change has been restored.[8] In April of 2021, President Biden invited forty global leaders to participate in the Virtual Leaders' Summit on Climate, where one of the key themes of the Summit was to discuss opportunities to strengthen capacity to protect lives and livelihoods from the impacts of climate change, address the global security challenges posed by climate change and the impact on readiness, and address the role of nature-based solutions in achieving net-zero emissions by 2050 goals.[9] Examples of these solutions include the use of biofuels and the development of bio-based materials that can reduce carbon emissions.

The Inflation Reduction Act (IRA) of 2022 will make an historic investment in clean energy, support domestic energy production and manufacturing, and reduce carbon emissions by roughly 40% by 2030. Combined with state action and forthcoming federal regulations, the IRA puts the U.S. within reach of its Paris Agreement commitment to cut emissions 50% to 52% by 2030.[9] The IRA will strengthen the U.S. economy by creating 1.3 million new jobs, and avoid nearly 4,500 premature deaths annually by reducing air pollution, both in 2030.[10] The IRA provides huge incentives for carbon capture, utilization, and sequestration (CCUS) projects and expands eligibility for carbon capture and sequestration credits, with the deadline for the beginning of construction extended to 2033 from the current 2026.[10] Besides supporting technologies that capture and store carbon dioxide released during power generation and industrial processes, the new bill also seeks to drive the deployment of direct air capture technologies, which extract CO2 directly from the atmosphere.[10]

The Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act, which President Biden signed into law on August 9, 2022, will provide unprecedented funding for K-12 science, technology, engineering, and mathematics (STEM) networks that support education and career development for students and adult learners seeking training in STEM fields. "This legislation represents months of bipartisan and bicameral negotiations," said Science, Space, and Technology Committee Chairwoman, Eddie Bernice Johnson. "We're building a diverse STEM workforce ready to tackle the challenges we face, we're strengthening our manufacturing capabilities, we're revitalizing American science and innovation, we're fighting the climate crisis, and so much more. And we're doing it all with the needs of each and every American in mind."[11]

Promoting public understanding about the need to address vulnerabilities due to climate is critical to igniting change. One campaign designed to influence this is the United Nation's Sustainability Development Goals, which includes free access to online educational resources for both formal and informal K-12 education programs to build awareness of global issues and the need for actions that improve and sustain the planet.[12]

Legislation that can advance workforce development includes the Infrastructure Investment and Jobs Act (IIJA), which required bipartisan support in both Houses to pass, contained $47 billion for climate resilience.[13] The IIJA provides approximately $310 million in grants to states, local governments, and utilities and provides funds to procure and use products derived from captured carbon oxides.[14]

Other politically-driven opportunities that can ignite the bioeconomy include active local government affairs committees that advocate for policies designed to promote bioindustrial manufacturing; state government funding policies that support investments in start-up initiatives; and federal government funding opportunities through agencies such as the Department of Defense and the Department of Energy. Jessica Hyland, Executive Director of the Iowa Biotechnology Association (IowaBio), described strategies that local government can implement to improve the bioeconomy in their state. She noted:

> ***"We have a very active Government Affairs Committee that sets up priorities each year, and then we go advocate on behalf of our companies and what they decide is important. Advocacy is a strong component of what we do. We offer the typical communications and newsletters, but during our legislative session, we are more focused on advocacy efforts and what's happening in politics and at the Capitol. We update our members every week on bills we're tracking, and through special legislative calls at key points during the session. We also have a strong social media presence, so we can amplify the voice of our members and what they are doing. We talk about the association, and what we're doing as well, so that people can better participate in the activities that we offer."***
>
> **Jessica Hyland**
> *Executive Director*
> Iowa Biotechnology Association (IowaBio)

Challenges

Political debates that paralyze decision-making present bottlenecks for moving the bioeconomy forward. The time and effort required to counter and resolve these debates can delay the passing of bills and result in gaps in funding that is necessary to implement solutions. Barriers include a lack of awareness of the need to support policies and initiatives that can impact these issues. According to Ken Alex, Director of the Climate Project at the Center for Law, Energy & the Environment at the University of California Berkeley:

> ***"From what I have observed, at the government and now at UC Berkeley, there is often quite a significant disconnect between the academic world and the industrial world and what goes on in policy."***
>
> **Ken Alex**
> *Director of the Climate Project at the Center for Law, Energy & the Environment*
> University of California Berkeley

The lack of public interest is apparent in a lack of voting for changes that can make a difference for future generations. At the local level, disconnects between state and federal policies present a challenge for government agencies and businesses.

Threats

The Ukraine war poses a significant threat to the safety and security of the bioeconomy. "Global conflicts heighten the inherent supply chain risks that inevitably influence the successful flow of materials worldwide. Manufacturing stoppages, capacity constraints within logistics channels, and port backlogs impact the availability of raw materials and finished goods. In the case of war, supply chain channels can be severely constrained or even shut down—further stressing vulnerable supply chain networks."[15] Supply chain issues, including those caused by COVID-19 and a lack of domestic manufacturing of semiconductor chips, could limit U.S. access to these critical resources. Gas prices, along with inflation, put added strain on the stability of supply chains that are necessary for sustaining the bioeconomy.

Other threats include ineffective immigration policies that do not support the recruitment and retention of scientists and experts from other countries who train in the United States, but then are forced to leave due to our immigration policies. Dr. Margaret Kosal, senior fellow at Savannah River National Laboratory's Nonproliferation Applied Science Center and Associate Professor at the Georgia Institute of Technology noted:

> ***"A lack of good internal cybersecurity practices in the bioindustrial manufacturing industry poses a significant threat. In bioindustrial manufacturing and in all of our U.S. manufacturing, we need to do a better job of investing in basic research...it's about ensuring that we are continuing to produce and to lead the world in terms of innovation that is at the edge and pushing back the bounds of knowledge."***
>
> **Dr. Margaret Kosal**
> *Associate Professor*
> Georgia Institute of Technology

Trends

Trends include a willingness to bring government agencies together to work collaboratively across agencies to accelerate progress. This is evidenced by the bipartisan support for recent legislation, such as the Inflation Reduction Act, that is expected to provide $60 billion that will help to create millions of new domestic clean manufacturing jobs. Another trend is the increase in outreach efforts to the public and to policymakers about advancements in the industry that support climate change and sustainability. In terms of workforce development, support for green jobs is a positive trend, as is the inclusion of STEM jobs in the strategic plans of federal agencies.

Recommendations

Recommendations include:

- Catalyze collaboration between industry, government, and local stakeholders
- Build awareness of the issues that need to be addressed to accelerate the bioeconomy
- Encourage stakeholders to vote for priority policies that can improve the bioindustrial manufacturing industry
- Build awareness about new legislation that impacts bioindustrial manufacturing and the bioeconomy

Economic Factors

Impacting the Bioindustrial Manufacturing Industry

Summary

The bioeconomy has be invigorated thanks to government support and investments in innovations that are spurring job creation in fields like synthetic biology. Current economic opportunities that are impacting the bioindustrial manufacturing workforce include historic legislation that will fund STEM education initiatives, programs that provide incentives that promote the use of bioproducts, and tax credit programs. Though the future bioeconomy is projected to be between $4 trillion and $30 trillion dollars globally, economic challenges to the industry include the high cost of startups, as they try to move new products from the lab to commercialization, and the substantial period of time it takes to develop a return on investment. Economic threats include the resurgence of COVID-19, which has forced costly delays and even shutdowns for many labs and manufacturing facilities. Trends include cost-saving new technologies that optimize the time it takes to test new innovations, increased public interest in science and discoveries using synthetic biology and recombinant DNA, the development of public-private partnerships, and an increase in opportunities for paid internships and fellowships offered by government agencies, including the Department of Defense.

Opportunities

- USDA BioPreferred Program
- Bioeconomy Development Opportunity Zone Designation
- Tax Credit programs for biorenewable chemicals
- Biofuel and feedstock incentives (USDA)

Challenges

- Low funding and high costs for bioindustrial manufacturing start ups
- Competition from other career fields
- Retention of workers while adapting to COVID-19 protocols
- Fragmentation of industry components that need to work in unison for product development

Threats

- Resurgence of COVID-19
- High turnover and recruitment costs
- Cybersecurity incidents
- Supply chain
- National security
- Patent and IP licensing

Trends

- Outreach to the public and policymakers about technological breakthroughs and advancements
- Cultivation of public and private partnerships
- Promotion of internships and fellowships through government agencies like the Department of Energy

Opportunities

As a result of recent legislation, the bioeconomy has received an infusion of funding from government sources that is likely to catalyze job growth in bioindustrial manufacturing. The CHIPS and Science Act will provide over $1.5 billion in fiscal year 2023 that will help advance important research and support standards development for industries of the future, including quantum information science, artificial intelligence, cybersecurity, privacy, engineering biology, advanced communications technologies, and semiconductors.[16] According to an announcement by the White House, it authorizes a significant increase in funding and expansion of the Manufacturing Extension Partnership (MEP) program, including to track supply chain disruptions and address the resilience of domestic supply chains; to authorize a significant increase in funding and expansion of the Manufacturing USA program to support over ten new competitively awarded institutes; and to support new activities to increase access to domestic manufacturing opportunities for traditionally underserved populations through both the MEP and Manufacturing USA programs.[16]

BioMADE is another example in which the government has invested, providing $87.5 million dollars over 7 years to build public-private partnerships with BioMADE members.[17] Additional investments include collaborative funding initiatives from government and industry partnerships, such as an $8.6 million initiative to improve U.S. STEM education, training, and research experiences through an historic collaboration between the National Science Foundation, the Bill & Melinda Gates Foundation, Schmidt Futures, and the Walton Family Foundation. NSF will be matching the money from the foundations for each funded activity.[18]

Other economic opportunities that can impact advancements in the industry include a focus on clusters and regional economic growth. Dr. Louise Bedwsorth, Executive Director at Center for Law, Energy & the Environment at Berkeley Law noted:

> ***"The state of California is advancing the Community Economic Resilience Fund. It is investing in regional collaboratives to bring people to the table to think about how to build regional economies. This includes consideration of workforce development and emphasizes a regionally-tailored approach to doing it. I think it is a big opportunity!"***
>
> **Dr. Louise Bedwsorth**
> *Executive Director at Center for Law, Energy & the Environment*
> Berkeley Law

The USDA BioPreferred Program incentivizes the production of biobased products and requires federal procurement to give preference to purchasing them. State governments and the private sector could further enhance such a procurement program through tax rebate incentives to encourage greater corporate procurement of local biobased products.[19] Public procurement is a strong catalyst for innovation, and today, many biomanufacturing products are at the same cost and performance parity as petrochemical based products.[19]

Hinman and Friedman[20] report that biomanufacturing has the potential to transform rural communities by potentially converting agricultural, forestry, or other resources into biobased products. These efforts have the potential to lead to job creation in renewable and clean energy and advancements in the development of biofuels and other products. These authors note that "Opportunities exist to sustainably incorporate rural waste resources, such as crop residues, forest residues, animal manure, and chicken litter into biomass processing."[20(pp67-74)] The challenge that remains is to develop renewable energy industries that operate sustainably and can be cost competitive with existing energy options.[21]

Other economic opportunities that can impact advancements in the industry include the cultivation of public and private partnerships; increased access to paid internships and fellowships through government agencies like the Department of Energy; and the development of bioindustrial manufacturing hubs in geographic areas that are in need of economic revitalization. For example, Cargill has partnered with Iowa State University and local community colleges to develop a pipeline for training the workforce needed to fill local jobs.

Challenges

Economic challenges to the industry include the high cost of startups as they try to move new products from the lab to commercialization, usually requiring a substantial period of time to develop a return on investment. Scaling bioindustrial manufacturing efforts is often inhibited by the capital intensity required to produce samples in order to move them into the marketplace. This is often referred to in manufacturing as the "valley of death," which is the metaphorical gap between a good idea and a successful product. The U.S. leads the world in innovations and inventions, yet the manufacturing capabilities and new products are often "stranded in the lab," or get developed in other countries.[22]

Another challenge is the fragmentation of the industry components that need to work in unison for product development. Similar to the cross-industry connections that have developed in the semiconductor industry, bioindustrial manufacturing is faced with the challenge of coordinating isolated efforts that are not cost effective.

Supply chain issues due to COVID-19 and the price of gas have created an economic strain on bioindustrial manufacturing companies. Examples include the high cost of feedstock transport and a lack of localized infrastructure to support the scaling of the production of products such as biofuels and bioplastics. Geographic challenges can add to the affordability and competitive advantage of new products. For example, in Brazil, sugar cane factories operate as a plantation system, with monocultures of sugar cane surrounding each refinery, while in the US, midwestern corn ethanol must travel by road and rail more than 100 km [62 mi] to markets on the east and west coast.[23] Retention of workers while adapting to COVID-19 protocols has also proven to be costly for the manufacturing sector, while recruiting a skilled workforce, especially highly trained engineers, is a challenge for companies who face competition and poaching from recruiters seeking skilled workers for other career fields.

Threats

Economic threats include the resurgence of COVID-19, which has forced costly delays and even shutdowns for many labs and manufacturing facilities, as well as supply chain issues. Expensive consequences from cybersecurity incidents pose another threat to the industry. The lack of a prepared and skilled biomanufacturing workforce has consequences for national security. Limited controls on patent and intellectual property licensing pose another threat. The development of new processes and machinery, such as proprietary bioreactors and biological printers, has become a strategy for protecting intellectual property in order to remain competitive. This requires an interdisciplinary team of highly skilled workers with a unique set of talents. Recruiters are burdened with finding and retaining employees that meet the needs of an evolving workforce.

Trends

Trends include the development of new cost-effective innovations that could revolutionize the biomanufacturing industry. DNA can now be sequenced relatively cheaply and shared over the internet in order to produce new self-replicating materials that can produce new product.[24] Scientists at Northwestern University are working on using cell-free systems and a rapid-prototyping system to accelerate the design of biological systems, that reduces the time needed to produce sustainable biomanufacturing products from months to weeks.[25] In a recent article, Michael Jewett, Walter P. Murphy Professor of Chemical and Biological Engineering and Charles Deering McCormick Professor of Teaching Excellence at the McCormick School of Engineering, who directs Northwestern's Center for Synthetic Biology stated: "For the first time, we show that cell-free platforms can inform and accelerate the design of industrial cellular systems. We accomplished in approximately two weeks what traditionally would have taken six to 12 months. Our findings will help accelerate the pace at which we can enable sustainable biomanufacturing practices."[25]

Other trends include the acceleration of outreach efforts to the public and to policymakers about advancements in the industry. For example, CRISPR and discoveries using synthetic biology and recombinant DNA are now more commonly on the news and in the media during prime time, which is building awareness about breakthroughs in the field.

Another cost-saving trend is the creation of co-lab spaces, such as LabCentral, which offers access to state of the art labs and supports developments in STEM, workforce training, and next generation entrepreneurship through its LabCentral Ignite initiative.[26] LabCentral is a Massachusetts non-profit company, founded in 2013 as a launchpad for high-potential life sciences and biotech start-ups.[26] Operating in two locations in Cambridge and on the Harvard University campus, LabCentral offers a network of fully permitted laboratory and office spaces for as many as 125 start-ups comprising approximately 1000 scientists and entrepreneurs.[26] Given the cost of the infrastructure that is needed for scaling products, sharing facility space and equipment makes economic sense.

Dr. Jill Zullo, Global Managing Director, BioIntermediates at Cargill, Inc., supports the idea of multi-use contractor manufacturing facilities. In a recent interview, she noted:

> ***"Access to multi-use contractor manufacturing facilities is critical to enabling start-up companies to move forward with getting products to the next level and can be very helpful for some of the smaller start-up companies. They can actually start the first launch of their products from such a place, and this could give their investors and their boards the confidence to go ahead and deploy capital."***
>
> **Dr. Jill Zullo**
> *Global Managing Director, BioIntermediates*
> Cargill, Inc.

Recommendations

Recommendations that, if implemented, could influence the economic factors impacting the industry include:

- Policymakers about technological breakthroughs and advancements
- Support for policies that create comparative advantage and expand domestic investment and employment[27]
- Increase coordination and communication of the opportunities available in the bioindustrial manufacturing workforce
- Create local training and employment opportunities that spur economic development and retention in the community
- Increase coordination and communication of the opportunities available in the bioindustrial manufacturing workforce
- Create local training and employment opportunities that spur economic development and retention in the community

Sociocultural Factors

Impacting the Bioindustrial Manufacturing Industry

Summary

Sociocultural factors, such as education, culture, attitudes, and interest, play a powerful role in workforce development. A lack of awareness of the educational opportunities available in biomanufacturing poses a significant barrier to developing the next generation of skilled workers. This could be reduced through exposure to career professionals in biomanufacturing through mentored internships and work-based learning opportunities. Recent federal and private investments in STEM education have the potential to provide resources that are needed to ignite interest in STEM careers. However, a lack of teacher training and the need to overcome the social effects of COVID-19, continue to pose a threat to workforce development. New strategies, including online-learning platforms, XR training resources, and open-access learning databases offer new ways to democratize access to job training that can help to prepare a future workforce that is ready to meet the evolving demands of the industry.

Opportunities

- Work-based learning
- STEM competitions
- Teacher professional development
- Degree programs
- Capstone projects
- Underserved recruitment programs
- Interactive learning platforms
- Incubators

Challenges

- Low student enrollment
- Untapped talent pools
- Need for teacher training in the use of advanced technologies and processes
- Low # of college graduates in biomanufacturing majors
- Non-inclusive company culture
- Need to align curriculum with current and future industry needs

Threats

- U.S. K-12 students rank below average in mathematics
- U.S. does not lead in science & engineering degrees
- Rejection of biotechnology
- Impact of COVID-19 on students - lost learning
- High talent turnover and competition
- Poaching of highly qualified employees

Trends

- Postsecondary–industry collaborations
- Biomanufacturing institutes
- State-led/regional biomanufacturing associations
- Recruitment from untapped talent pools
- Open access learning databases
- XR training resources

Opportunities

The CHIPS and Science Act provides a significant investment in STEM education and research that is likely to bolster opportunities for students and attract them to careers in bioindustrial manufacturing.[27] It authorizes the NSF to:

- Double the NSF budget over five years, including $13 billion for STEM education
- Formally establish NSF's new Directorate for Technology, Innovation, and Partnerships to foster use-inspired and translational research and provides an authorization of $20 billion over five years. The bill identifies an initial list of societal, national, and geostrategic challenges—including "inequitable access to education, opportunity, or other services"—and establishes ten key areas of technology for the directorate. It also establishes Regional Innovation Engines, which are encouraged to partner with other organizations to inform research directions and account for the societal implications of the research.
- Support PreK–12 informal STEM opportunities, such as awards for "research on effective approaches to engaging students in PreK–12, including students from groups historically underrepresented in STEM and rural students" with a focus on "innovative before-school, after-school, out-of-school, and summer activities that are designed to encourage interest, engagement, and skills development in STEM."
- Scale innovations in PreK–12 STEM education by establishing Centers for Transformative Education Research and Translation that bring together partners to facilitate the widespread and sustained implementation of promising, evidence-based STEM education practices.[27]

Early exposure to STEM activities that engage students and their families can spark interest in and promote understanding of biomanufacturing career pathways. Educational opportunities that can expose students to the skills needed in the workforce range from hands-on learning experiences at museums to internships and capstone projects at higher educational institutions.

The Illumina Corporate Foundation provides students, teachers and families with genomics literacy resources, such as videos, virtual field trips, and downloadable coloring books that focus on understanding DNA. These materials build awareness of the multidisciplinary science and engineering concepts that are utilized in biomanufacturing careers. Vanessa Light, Corporate Citizenship Manager at Illumina, stated:

> ***"One of our campaigns, "The Future is Bright", is around DNA Day on April 25th; it is both an outreach and an employee engagement program. During this time, teachers were looking for hands-on opportunities, and we provided strawberry DNA extraction kits that can be used in grades K–12. At the high school level, we virtually connect classrooms with our employees to have career chats and even do experiments side-by-side with our employees."***
>
> **Vanessa Light**
> *Corporate Citizenship Manager*
> Illumina

Studies suggest that competitions are an effective way to foster career interest in specific STEM careers.[28,29] STEM competitions that engage students in grades 6–12 include the U.S. Science and Engineering Festival's X-STEM All Access Virtual Conference and the Regeneron International Science Fair.

The International Genetically Engineered Machine Competition (IGEM) is a synthetic biology competition for both university and high school level students designed to inspire learning and innovation in synthetic biology through education, competition, and by maintaining an open library of standard biological parts, the Registry of Standard Biological Parts.[30] Synthetic biology (SynBio) is the science of "programming" organisms with synthetic or artificial DNA that biologists develop by conducting metabolic engineering.[31]

Two years of survey data collected from undergraduates after their iGEM experiences in 2007 and 2008 suggest that both learning and identity as a biological engineer increase as a result of iGEM.[29] Another report from 2017 found that many student-led teams are able to build on the fundamentals of synthetic biology to generate a wide range of useful bioproducts.[32] In doing so, students are training themselves for future careers in STEM and expanding the field of synthetic biology.[32]

The demand for skilled manufacturing technicians, process technicians, and bioprocessing engineers offers career opportunities that vary in educational requirements. Education that prepares students for the future requires that the educators themselves build confidence and competence in foundational skills that students will need to secure quality jobs in bioindustrial manufacturing. Resources that provide teachers with student-centric curriculum and professionally-relevant training include content and programs from the BioBuilder Educational Foundation.

BioBuilder's Founder and Executive Director, Dr. Natalie Kuldell, noted:

> ***"I'm so grateful that BioBuilder started 10 years ago with a teacher professional development workshop at MIT. Of course, in the decade since then, we have adapted it. Now we offer a hybrid model. It starts with pre-recorded lectures that teachers can watch anywhere and at their own pace, using an online interactive platform. And then we ship laboratory kits to teachers at their schools and synchronously run two days of lab activities with them. We do the experiments online in our labs and they log-in while they try the labs in their schools. This model helps them know that they have everything they'll need and builds confidence that they can teach this experiment to their students."***
>
> **Natalie Kuldell**
> *Founder and Executive Director*
> BioBuilder

Golden LEAF Biomanufacturing Training and Education Center (BTEC), located on the North Carolina State University's Centennial Campus, is a cross-disciplinary instructional center that provides educational and training opportunities to develop skilled professionals for the biomanufacturing industry. Led by Executive Director, Dr. Gary Gilleskie, BTEC provides undergraduates, graduate students, and working professionals hands-on learning opportunities with the latest bioprocessing and biomanufacturing technologies. BTEC also provides bioprocess development and analytical services to a wide range of customers from academia and industry.[33]

A curated list of educational programs that build awareness and promote the development of the skills needed in bioindustrial manufacturing are described in **Table 1** in the Appendix.

Challenges

Challenges impacting workforce preparation include sociocultural factors such as students' lack of understanding about the types of jobs that exist in bioindustrial manufacturing. Many students are unaware of career paths that lead to becoming a bioindustrial technician, bioengineer, or synthetic biologist. Julie Gonzalez, Biotechnology Program Chair at Des Moines Community College in Iowa stated:

> ***"My most pressing challenge is recruitment, catching students early and helping them get in the right classes. I have met students in their final semester, who tell me that what they really wanted to do was work in a lab but they did not know how and nobody along their pathway had known enough about the opportunities to guide them."***
>
> **Julie Gonzalez**
> *Biotechnology Program Chair*
> Des Moines Community College in Iowa

Dr. Corin Slown, Associate Professor, Science Education at California State University Monterey Bay explained:

> ***"I think another challenge is just awareness of the career opportunities. It's almost like a three-stage rocket: There's the prep, so that the student has awareness of what the career is. There is a connection piece, where they start to see themselves potentially as someone exploring and or traveling along a path that would include that industry. And then there's a human or personal connection to the work itself. So sometimes we make progress on that first stage, but then there are barriers to the second or third stage."***
>
> **Dr. Corin Slown**
> *Associate Professor, Science Education*
> California State University Monterey Bay

Another persistent challenge is low enrollment in postsecondary programs that have suffered from the impact of COVID-19. Resistance to returning to campus at some academic institutions has resulted in fewer students enrolling, as well as a teacher shortage that is causing a crisis for many school districts.

Developing students' skill proficiency in the use of these technologies is challenging due to a lack of well-equipped labs. The cost of lab equipment, such as bioreactors, can limit access to facilities that meet industry standards for training students and teachers. Other challenges to developing and retaining a resilient workforce include:

- Non-inclusive company culture that is unwelcoming to women and underrepresented groups
- Lack of industry-aligned curriculum designed to meet current and future industry needs
- Lack of industry partnerships that provide paid internships to students, especially for those who are under 18 years of age

Threats

Threats that hinder efforts to expand the bioindustrial manufacturing workforce include the rejection of careers in the field due to parent and guidance counselors' perceptions, and a lack of student persistence in pursuing bioindustrial manufacturing job opportunities. A resurgence of COVID-19, which contributed to reduced enrollment in post-secondary institutions and hampered working conditions in manufacturing settings, continues to pose a threat to workforce development. Another threat is the skills gaps in mathematics and science, amplified by COVID-19, which makes it difficult to diversify the workforce and increase the pipeline from high school training programs to higher education, job placement, and advancement.

Competition from other lucrative fields, such as computer science, is another threat to building the workforce, as is the high degree of turnover in jobs where there is a culture that is not conducive to developing careers for women and members of underrepresented groups. Poaching of highly skilled engineers and doctoral-level researchers has become the norm for companies seeking to hire the best and most qualified candidates.

Trends

One trend that is decreasing the time that it takes to become workforce ready is the use of XR technologies, such as virtual reality, augmented reality, and mixed reality. The benefits of using XR technologies in training students and employees include increased safety, lower costs, and the ability to work remotely while feeling as though they are present in the physical workplace.[34] XR makes it possible for educators to maximize student engagement through the use of contextual learning environments, tracking of eye and body movement, and the ability to customize the virtual experience.[35]

To reduce the hiring costs of a technology adept workforce, many companies are helping their employees acquire the skills they need for new jobs and upward mobility.[36] A recent publication by McKinsey Global Institute (2021) reported:

"Studies have found that retraining existing employees with proven track records is typically far more cost-effective than hiring new people… Other possible measures include changes in hiring practices that put the focus on skills rather than academic degrees. This can expand the pool of available candidates and increase diversity for companies, while helping to ease the broad workforce transitions that will play out across all countries. Google, Hilton Hotels, Ernst & Young, and IBM are among a growing number of employers that have changed job postings to remove degree requirements and focus on skills; they have seen marked increases in new hires without college degrees for some roles. Finally, companies could give greater consideration to diversity and inclusion to counter the regressive impact of COVID-19. Business leaders may increase their focus and innovation in hiring and retaining diverse groups".[36]

The use of micro-credentials and performance-based certifications is gaining popularity, in order to provide evidence of the key performance indicators required in the workplace. Bioscience Core Skills Institute (BCSI) provides workforce skills assessment and digital micro-credentialing that is valid, reliable, and trusted by the bioscience industry.[37] Working with educational and industry partners, BCSI provides assessment opportunities and documentation of skills. Co-founder and Chief Executive Officer Angela Consani described the need for performance-based skills assessment:

> ***"All industries do a lot of assessment of content knowledge. And they attempt to assess character using things like interviews. But when it comes to being able to figure out what an individual can actually do, that's a big gap between education and jobs. Particularly in the biotech industry, where skills are such an important part of the job, where there are physical movements that someone must be able to perform in a certain sequence and done in a certain way in order to keep from costing companies hundreds of 1000s of dollars for mistakes and deviations. So I would say that is the gap, the assessment of skills, it's not something that's done prior-to-hire across the entire industry."***
>
> **Angela Consani**
> *Co-founder and CEO*
> Bioscience Core Skills Institute

Recommendations

Strategies for diversifying the biomanufacturing workforce include focusing recruitment efforts on untapped talent pools, including veterans, to increase the number of diverse workers that can meet the growing demands of the industry. Cultivating industry and academic collaborations can help support up-to-date, industry-aligned curriculum, teacher training, and virtual and workplace mentoring experiences. Creating more state-of-the-art biomanufacturing institutes like BTEC, that partner with higher education institutions, is another strategy that can infuse growth in the number of trained students and the prepared faculty that are needed to teach them. Finally, recruiting inclusive industry experts, who can serve as mentors, support capstone projects, and provide paid virtual and workplace internships will help prepare students for careers in biomanufacturing.

Additional recommendations from stakeholders who attended the BioMADE STEMconnector Innovation Lab in July 2022 are provided in **Table 1** in the Appendix.

Technological Factors

Impacting the Bioindustrial Manufacturing Industry

Summary

Technological innovations and new product offerings in biomanufacturing influence the type of skills that job seekers must acquire to propel the industry forward. In the past decade, the rate of new discoveries has accelerated due to the invention of tools that allow companies to transcend previous methods by leveraging resources that are cost effective and efficient in the production of novel materials. Breakthrough technologies have changed the way businesses operate and have created the need for a technologically-prepared workforce with interdisciplinary capabilities in domains such as artificial intelligence, automation, and streamlined gene sequencing. Challenges that need to be overcome include the cost of basic research and scaling that will support launching new innovations into the marketplace and the need for trained technicians, scientists, and researchers who can test and refine products, so that they can be commercialized. Threats to the industry include gaps in biocybersecurity, competition for highly trained professionals with doctorate degrees, and a need to protect the intellectual property of new advancements.

Opportunities

- Online learning models
- Robotics
- Automation
- Artificial intelligence
- Machine learning
- Partnerships to increase access to new technologies
- Investment in research that supports new technologies

Challenges

- Fear that automation will replace jobs
- Cost of funding start-ups that use innovative technologies
- Limited access to new and advanced bioindustrial manufacturing equipment for testing and scaling

Threats

- Cybersecurity
- Biosecurity
- Industrial control systems
- Intellectual property
- Lack of infrastructure to support the safe use of new technologies

Trends

- Automation
- AI
- Platforms
- Access to shared workspaces, repositories, and equipment
- Biomanufacturing in Space

Opportunities

The Fourth Industrial Revolution, named by Klaus Schwab, author of a book with the same title, is an era marked by the technological revolution that is blurring the lines between the physical, digital, and biological sphere.[38] The industry-changing impacts of Industry 4.0 advancements are likely to be seen and experienced in terms of changes to: (a) the design of manufacturing work; (b) the manufacturing worker experience; (c) critical worker knowledge, skill, ability, and competency requirements; and (d) numerous other talent management considerations involving talent acquisition, retention, and training/development needs.[39] A recent article on the Bio Revolution by the McKinsey Global Institute (2022) reported that a wave of innovation is being enabled by advances in biological sciences accelerated by developments in computing, data analytics, machine learning, AI, and biological engineering. The report grouped innovations into four arenas: biomolecules, biosystems, biomachine interfaces, and biocomputing.[40]

The National Science Foundation's Future Manufacturing website[41] states:

> "The next generation of technological competition in manufacturing will be dictated by a combination of the use of computation to ensure the reliable translation of product designs to manufacturing plans; process controls that provide assurances that the execution of those plans will produce products that meet specifications; inventions of new materials, chemicals, devices, systems, processes, machines, and design and work methods; and new social structures and business practices. Fundamental research will be required in robotics, artificial intelligence, biotechnology, chemical conversion processes, materials science, sustainability, education and public policy, and workforce development to lead this global competition".[41]

Examples of technologies that have the potential to advance biomanufacturing include artificial intelligence, which are enabling automation and boosting efficiencies in strain engineering. Automation technology, combined with faster and more reliable engineering techniques, has resulted in the emergence of robotic 'cloud labs' where digital information is transformed in DNA then expressed in some target organisms with very high through-put and decreasing human oversight.[42]

Ginko BioWorks is harnessing the power of automation to scale testing in biomanufacturing. Ginkgo's foundries currently rely on software and robotics to automate work on organism design across the flavor and fragrance, enzyme and agricultural industries.[43]

The term "clustered regularly interspaced short palindromic repeats" (CRISPR) has recently become synonymous with the genome-editing revolution.[44]

Dr. Bryn Adams, Branch Chief, Synthetic Biology Tools Branch, at the DEVCOM Army Research Laboratory note:

> ***"Probably the biggest innovation is going to be CRISPR/Cas 9 which enables very precise genetic editing and control at a level that we haven't been able to get at before. One of the key enabling technologies is artificial intelligence and machine learning, specifically in biotechnology and synthetic biology, which produce extremely large amounts of data. So large, that it's not humanly possible to work through the data and find trends, much less make the predictions that AI and machine learning can do. I think it's going to be critical that we tap into that in order to be able to create accurate models to drive the research in a cost-effective and time-effective manner."***
>
> **Dr. Bryn Adams**
> *Branch Chief, Synthetic Biology Tools Branch*
> DEVCOM Army Research Laboratory

Challenges

Challenges that come with technological innovation and Industry 4.0 include the need for multifaceted, interdisciplinary training that prepares employees for deploying and managing new technological manufacturing processes. As noted by Meyers and Cunningham (2021), "Unfortunately, not all manufacturing organizations are equally ready to adopt and benefit from Industry 4.0; there is a real and significant need for scalable, technology-focused training that can help to upskill and reskill incumbent and emergent workers in manufacturing organizations of all sizes.[39]

The cost of funding start-ups that use these innovative technologies presents another challenge, as does the limited access to new and advanced bioindustrial manufacturing equipment for testing and scaling. A lack of infrastructure to support the safe use of new technologies presents another challenge.

Threats

Biosecurity threats need to be considered in the wake of disruptive innovations that are accelerating the process of developing new products. Using synthetic biology techniques, it is possible for a nefarious actor to acquire a viral pathogen with chemically synthesized pieces, versus having to acquire samples of pathogens from an environmental source or from another laboratory.[45]

Other threats include a lack of robust internal cybersecurity practices in the bioindustrial manufacturing industry that need to be better understood. As manufacturing operations are increasingly networked, the risks that a controller or sample analysis instrument could be attacked and manipulated by outside entities requires protective strategies to prevent vulnerabilities.[46]

During a recent Built with Biology podcast (2022), James Diggans, Head of Biosecurity at Twist Bioscience explained: “Cybersecurity, biosecurity, and biosafety have become critical in the COVID-19 era. Biosafety, you can think of as kind of a set of practices and protocols that are really focused on protecting individuals working in a lab with biological organisms. So those practices might govern what kind of gloves and masks to wear or how to decontaminate a work surface once you finish an experiment. And importantly those biosafety measures apply to those well-trained individuals who are doing work that they are explicitly authorized to carry out. Biosecurity, in contrast, is really focused on preventing intentional misuse of biological materials to cause some form of harm. So it is trying to answer two questions: Can this biological material that I am thinking about be misused, and if so, how can we ensure that this material is only provided to individuals who will use it responsibly?”[47]

Trends

Trends that are attracting interest in biomanufacturing include an increase in publicity and social media involving CRISPR Cas 9 and discoveries using synthetic biology and recombinant DNA that are now more commonly on the news during prime time.

Transformative capabilities in synthetic biology that are revolutionizing the biomanufacturing industry include new processes for synthesizing DNA. Twist Bioscience has developed a proprietary semiconductor-based synthetic DNA manufacturing process featuring a high-throughput silicon platform that miniaturizes the chemistry necessary for DNA synthesis, while reducing the cost and amount of required chemicals. This innovation increases the efficiency needed to produce reaction volumes by a factor of 1,000,000 while increasing throughput by a factor of 1,000, enabling the synthesis of 9,600 genes on a single silicon chip at full scale. Traditional synthesis methods produce a single gene in the same physical space using a 96-well plate.[48]

Interest in space travel has been invigorated by the increase in planned missions to the Moon and to Mars. Biotechnology has emerged as a promising approach to increase mission resilience, flexibility, and efficiency by virtue of its ability to utilize in situ resources and reclaim resources from waste streams.[49] Space bioprocess engineering (SBE) is an emerging multi-disciplinary field to design, realize, and mange biologically-driven technologies specifically with the goal of supporting life on long-term space missions.[50] Astronauts might one day grow and eat genetically modified plants to ward off disease associated with long spaceflights. For example, researchers at the University of California, Davis, College of Engineering have developed a transgenic, or genetically modified, lettuce producing a drug to protect against bone density loss in microgravity.[51]

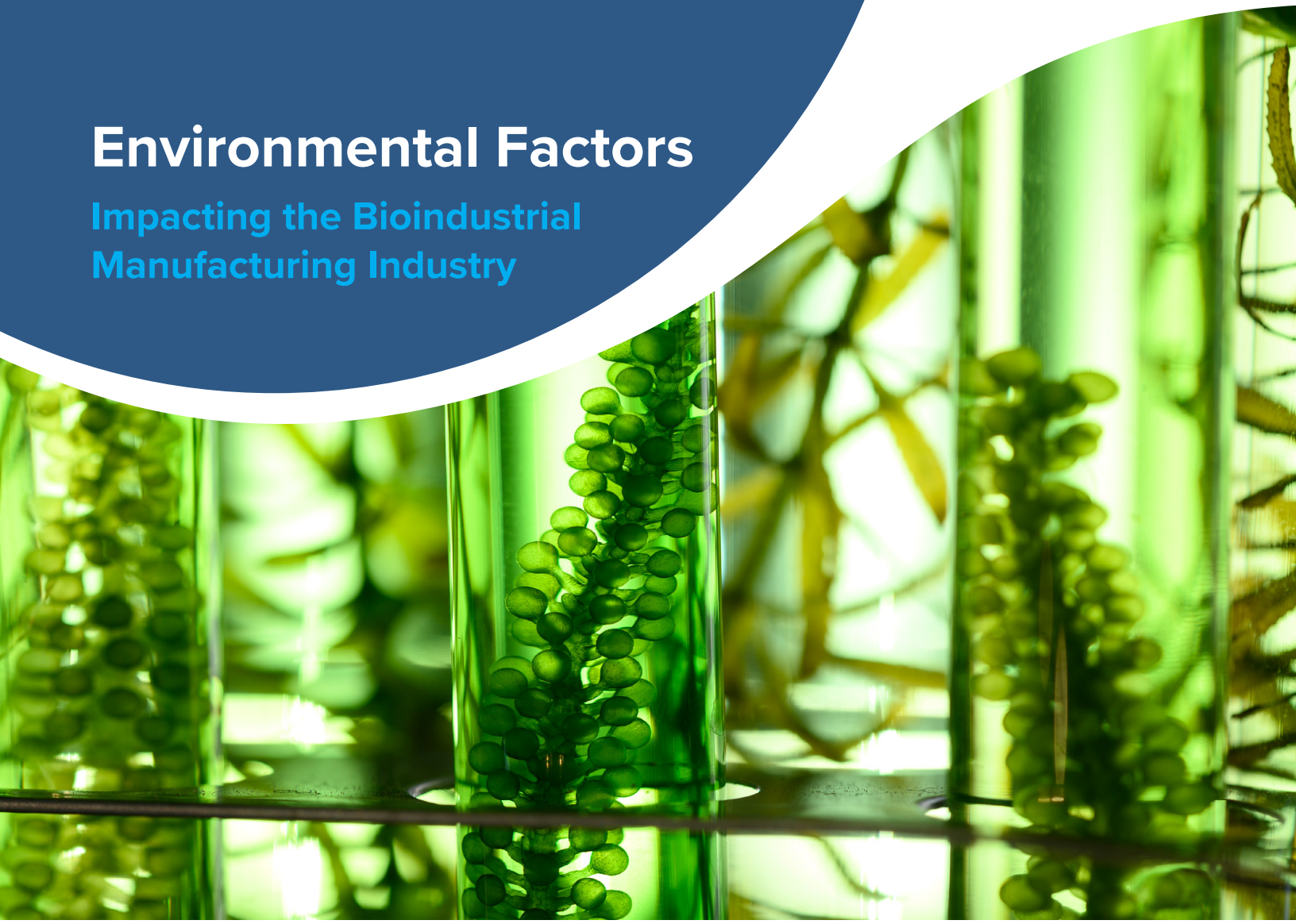
Recommendations

Recommendations that have the potential of developing the future bioindustrial manufacturing workforce include:

- Increase access to opportunities for interdisciplinary technical training using cutting-edge technologies
- Promote awareness of automation, biosecurity, engineering biology, and synthetic biology careers among marginalized and underrepresented groups
- Develop the infrastructure needed to create new bioproducts using safe processes and controls that prevent misuse

Environmental Factors

Impacting the Bioindustrial Manufacturing Industry



Summary

Since rejoining the Paris Agreement in January of 2021, America's commitment to address threats from climate change has been restored. The Inflation Reduction Act of 2022 represents the most aggressive action to combat the climate crisis and improve American energy security in our nation's history.[52] Bioindustrial manufacturing can impact climate change by creating new materials or sustainable alternatives to existing petroleum-based materials and producing materials with physical and chemical properties that are not currently available. Innovations in the development of sustainable products, such as bio-based plastics, leather alternatives, rubber substitutes, and composites provide opportunities for jobs involving the creation of eco-friendly products. Challenges include the need for industry to integrate sustainability-related practices that reduce carbon emissions, as well as land and water usage. Misinformation about climate change threatens the promotion of public support that is necessary for transitioning to a more sustainable bioeconomy. Biomanufacturing trends that can preserve the environment include the production of new bio-based materials, alternative proteins, and carbon sequestering.

Opportunities

- Public interest in mitigating climate change
- Innovations in bioplastics and biofuels
- Carbon credit incentives
- Plant-based alternatives to meat
- Bioeconomy Development Opportunity Zones: biomass feedstocks

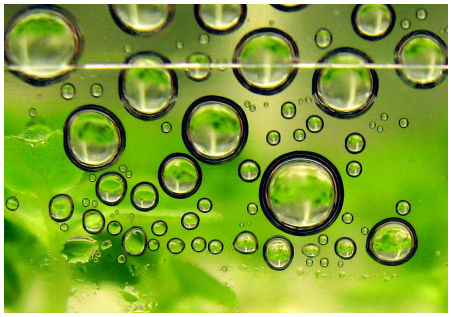
Challenges

- Awareness of new synthetic biology methods vs traditional agriculture
- Climate change and meeting Paris agreement of carbon neutral by 2050
- Reducing carbon footprint
- Reduction of agricultural land uses

Threats

- Misinformation about climate change
- Climate change disruptions to the supply chain
- Cost associated with climate change initiatives
- Lack of action

Trends



- Biofuel production
- Alternative proteins
- New bio-based materials and composites
- Carbon sequestering

Opportunities

The devastating impacts of climate change have increased awareness of the urgent need to transition to a more environmentally resilient society. Positive shifts in attitudes around sustainability have caused a surge in environmentally conscious behaviors that range from reducing water use and land use to increased understanding of the impact of leaving a carbon footprint on the planet. In April of 2021, President Biden invited forty global leaders to participate in the Virtual Leaders' Summit on Climate, where one of the key themes was to discuss opportunities to strengthen capacity to protect lives and livelihoods from the impacts of climate change, address the global security challenges posed by climate change and the impact on readiness, and address the role of nature-based solutions in achieving net zero emissions by 2050 goals.[9]

The Inflation Reduction Act and the CHIPS and Science Act of 2022 provide needed investments in the bioeconomy that support reducing dependence on fossil-fuels and provide opportunities for jobs involving the creation of eco-friendly products. Sustainable materials and biobased chemicals that align with the principles of a circular economy, can have a positive impact on the environment and secure the future for the next generation. These include products that are designed with processes aimed at zero waste, use of renewable energy, reuse and return to the biosphere, and restoration to replace the end-of-life concept.[53]

Unlike the linear economy, in which companies mine natural resources to make products that are designed to be discarded, the circular economy closes the loop. Materials and products are designed to be more durable, reusable, repairable, and recyclable, thereby extending product life cycles and curbing waste. This approach can make a tremendous impact on the environment.[54] A study published in Science[55] found that plastic use can be reduced by nearly 80% in the next 20 years, in part, by adopting circular economy practices across the supply chain. Examples include the development of biofuels, bio-based plastics, and sustainable food products, as well as innovations in optimal carbon sequestering practices.

Creating renewable sources of bioenergy and biofuels to substitute for fossil-based sources presents an opportunity to develop new products that can reduce dependence on fossil fuels. One example, described by Kruger et al., (2022) is the use of algae, as a nascent agricultural bioenergy crop, which promise faster growth rates and higher fuel yields per unit land area than terrestrial crops. However, algal biofuels remain in a pre-commercial state, with modeled fuel selling prices indicating commercial production with current technology would be considerably more expensive than either petroleum-based fuels or terrestrial crop-based biofuels.[56]

Biofuels are produced from biomass, which are materials derived from a living or recently living organism, including plants, grains, vegetable oils, and animal-based oils. These types of materials are commonly referred to as feedstocks.[57] Because biofuels are derived largely from plants, these fuels are a renewable resource that can be replenished naturally with the passage of time, unlike crude oil. They can be produced in the U.S., which reduces our dependence on foreign oil and helps to shield American consumers from fluctuating global oil prices. Annual global demand for biofuels is set to grow 28% by 2026, reaching 186 billion liters.[58]

Plastic pollution is a pervasive and growing environmental problem around the world. To avoid a massive build-up of plastic in the environment, coordinated global action is urgently needed to reduce plastic consumption; increase rates of reuse, waste collection, and recycling; expand safe disposal systems; and accelerate innovation in the plastic value chain.[55] Zion Market Analysis estimates the bioplastics market will surge from $10.51 billion in 2021 to some $28.94 billion in 2028.[59] Cargill, in partnership with NatureWorks and PTT World Chemical, produces polylactic acid (PLA), [a 100% biosourced plastic], created by bioplastic produced by fermenting sugar from corn and sugar cane.[60]

In order to meet the increasing demand for biogenic raw materials, the options of expanding agricultural land, land efficiency, plant breeding, and reducing the cultivation of feed for meat production have been investigated.[61] A recent study showed that the green house gases produced by meat production are two times that of plant production.[62] A transition away from animal meat would bring huge benefits for the environment, for public health, for the ethical treatment of animals, and potentially for workers and the economy.[63] According to the Good Food Institute, “Cultivated meat is meat produced directly from cells. The process of cultivating meat uses the basic elements needed to build muscle and fat and enables the same biological process that happens inside an animal. Cultivated meat is identical to conventional meat at the cellular level.”[64] Products produced by companies like Mission Barns include meat that is grown in a lab from cultured animal cells, rather than from raising and slaughtering whole animals. The idea is to create real meat, but in a way that is more sustainable, ethical, and healthy.[65]

The current retail market for plant-based foods is valued at $5 billion.[66] A 2020 study by the Plant Based Foods Association (PBFA) and Kroger found that in the Midwest region, where a flexitarian diet is growing in popularity, plant-based meat sales were up 32% when placed in the meat department.[67]

Impossible Foods Inc. is a company that develops plant-based substitutes for meat products. The company’s signature product, the Impossible Burger, was launched in July 2016.[68] In partnership with Burger King, Impossible Whoppers started to be sold nationwide by the burger chain in summer 2019. The product’s meat flavor is attributed to the use of heme. “Heme is an iron-containing molecule

found in every living organism—both plants and animals. Impossible Foods' scientists discovered early in their research that heme is what makes meat taste like meat. Impossible products get their heme from the protein soy leghemoglobin, which can be naturally found in soy roots. Impossible Foods produces soy leghemoglobin through genetic engineering and fermentation."[68]

The plant-based food market grew almost twice as fast as the total U.S. retail food market, which increased 15% in 2020 as COVID-19 shuttered restaurants and consumers stocked up on food amid lockdowns.[69]

Table 2 in the Appendix provides a list of examples of plant-based food companies that are changing the food industry and improving the environment.

Challenges

The challenge that remains is to develop renewable energy industries that operate sustainably and can be cost competitive with existing energy options.[70] Scaling the development and manufacturing of biofuels[71] has been challenging and more expensive than either petroleum-based fuels or terrestrial crop-based biofuels.[57] Cost-effective and energy-efficient integrated systems are needed to support and expand the biofuels infrastructure in order to meet the challenges of scale, and will require investment in novel technologies, efficient value chains, and socioeconomic and policy frameworks.[72]

Another challenge is the cost of feedstock transport and a lack of infrastructure to support the scaling of the production of biofuels. The price of gas and inflation pose a financial hardship for supply chain management.

The transition to sustainable foods is challenged by a resistance to change. Altering behaviors, such as dietary practices to include more environmentally friendly food choices, is challenging because many foods are connected to lifestyle, tradition, and culture. While some consumers are enthusiastic about the prospect of reducing the health risks, environmental harms, and animal welfare implications associated with conventional meat production, others have concerns about the product's taste, price, safety, and naturalness.[73] Replacing meat with alternative proteins will require time, effort, and persuasive marketing, as well as the development of products with the flavor and texture that is appealing to the customer.

Threats

Climate change poses a threat to the environment, potentially disrupting supply chains and increasing the cost of doing business. Recent flooding, fires, and catastrophic storms have damaged entire regions of the country in the past year, causing loss of life, homes, and business.

Misinformation about climate change and the urgent need to address it has prevented many stakeholders from taking action. The cost associated with climate change initiatives and the production of sustainable products like biofuels may prevent them from being economically competitive. Fossil fuel subsidies actively create an uneven economic playing field[71] and provide an obstacle for the promotion of biofuels.

Recommendations

Recommendations for addressing environmental factors that influence the biomanufacturing industry include the promotion of cost-effective and energy-efficient integrated systems to support and expand the biofuels infrastructure in order to meet the challenges of scale.[71] Strategies for building consumer awareness of the benefits of alternative proteins will require social media support and an investment in marketing, but have the potential of revolutionizing the food industry. Lastly, investing in research that focuses on sequestering carbon emissions is another recommendation that, combined with the development of alternative energy sources, could improve the planet.

Trends

The creation of new products from natural materials is a trend that is impacting several industries. Examples include leather-like products that are produced from mushrooms and rubber substitutes made from dandelions. These products replace dependence on animals and promote sustainability.

Increased use of biofuels using algae and other innovations is a trend that could make a powerful impact on the environment and the biomanufacturing industry. ExxonMobil and Viridos, previously called Synthetic Genomics, have been working together for over a decade, when ExxonMobil opened a greenhouse facility in La Jolla, California, to test algae as a biofuel feedstock.[74] Shell announced it plans to produce about 2 million tonnes of sustainable aviation fuel a year by 2025.[74]

Legal Factors

Impacting the Bioindustrial Manufacturing Industry

Summary

The escalating infusion of new products entering the bioindustrial manufacturing marketplace provides a wealth of opportunities for careers in fields such as synthetic biology, engineering biology, and bioprocessing. However, the increased scale and complexity of these products is putting a strain on the existing regulatory system. Cybersecurity, biosecurity, and biosafety have become critical in the COVID-19 era.[47] The trend toward sharable registries and data repositories brings with it the need for efficient patent and licensing policies, as well as cybersecurity plans that protect the information from bad actors that pose a threat. There is a need for a long-term strategy to assess risks associated with future products, as well as determine what capabilities, tools, and expertise are needed for oversight.

Opportunities

- New markets and products entering business to business models
- Increased access to advanced molecular biology tools and peer-to-peer sharing platforms
- Rapid prototyping and development processes
- Availability of buying and selling new biotechnology tools

Challenges

- Increased scope, scale, and complexity of biotechnology products that are being submitted for regulatory approval
- Need to update regulatory frameworks
- Concerns over the safety and ethics of various biotechnologies

Threats

- Future products pose a significant potential stress to the existing regulatory system
- Need for biosecurity and cybersecurity processes
- Lack of efficient patent and licensing processes and policies
- Lack of efficient regulatory policies and standards

Trends

- New products that leverage crowd-sourced designs
- Sharable registries and data repositories
- Awareness of biosafety issues
- Development of frameworks to promote standards

Opportunities

Opportunities for new products entering the bioindustrial manufacturing marketplace are on the rise. The National Science Foundation expects "the next generation of technological competition in manufacturing will be dictated by a combination of the use of computation to ensure the reliable translation of product designs to manufacturing plans; process controls that provide assurances that the execution of those plans will produce products that meet specifications; inventions of new materials, chemicals, devices, systems, processes, machines, and design and work methods; and new social structures and business practices".[41]

Increased access to advanced molecular biology tools, rapid-prototyping systems, and cloud-based platforms with analysis capabilities are creating opportunities for researchers and biomanufacturing companies to develop new innovations at greater speeds than ever before. Datasets relevant to bioindustrial manufacturing span genetics, omics, chemistry, bioprocessing, scale-up, and downstream processing, as well as associated performance metrics and economic analyses.[75] Sharable registries and data repositories elevate the need for efficient patent and licensing policies, as well as cybersecurity plans that protect the information.

The potential harm that can result from high-risk technological advancements raises ethical concerns that need to be addressed so that potential misuse can be controlled. Ethical issues present opportunities to examine if the risks outweigh the benefits of some innovations.

Challenges

The increased scale and complexity of new products is putting a strain on the existing regulatory system. There is a lack of efficient policies to handle the demand and a need to update existing regulatory and risk assessment frameworks.

Biosecurity is another challenge that requires attention. Developing ways to encourage companies to invest in biosecurity processes is important to protecting their products and their customers.

With the wave of new innovations circulating in the marketplace, another consideration is the protection of intellectual property that does not restrict dissemination or raise barriers to entry, yet protects traditional natural products from inequitable commercialization.[71]

Threats

The catastrophic impacts of cybersecurity breaches from domestic and foreign entities threaten the safety, privacy, and security of biomanufacturing companies that may be unprepared for an attack. The need to protect and continuously monitor information technology resources and data has become paramount to ensuring that valuable biomanufacturing assets are usable and sound. Other threats include intellectual property infractions, theft of proprietary processes, and patent infringement.

Given the war in Ukraine and the recent pandemic, threats related to the use of harmful biological weapons are more of a concern than in the past. Protection from biothreats that pose risks to the environment, humans, and crops are also a threat to national security.

Trends

Trends in biosecurity include cloud computing, which can provide automated monitoring systems that can send instant alerts to security technicians for a broad spectrum of vulnerabilities, in addition to storing and tracking data in more easily digestible formats.[76]

The National Institute of Standards and Technology's (NIST) has begun the process of updating the NIST Cybersecurity Framework to keep pace with the evolving cybersecurity landscape.[77]

The NIST Risk Management Framework, which includes seven security-related measures designed to assure system,[76] includes seven security-related measures designed to assure system,[76] Other guidelines include the FAIR Data Principles that make data findable, accessible, interoperable, and reusable.[78]

Recommendations

Recommendations for safeguarding biomanufacturing resources include: building awareness of cyber and biosecurity threats; encouraging companies to implement internal risk assessment practices; developing efficient approaches to risk analysis; and leveraging existing statutes and practices to refine regulatory policies. Other recommendations include: the development of a coordinated plan for exploring efficient approaches to risk analysis; leveraging existing statutes and practices to refine regulatory policies; and the promotion of cross-agency collaboration to determine and interpret which entities have legal authority over the regulation of future products.

Conclusion

This environmental scan of the bioindustrial manufacturing landscape provides insights about the powerful dynamics that are at play in this rapidly evolving field and unveils opportunities for careers that range from creating environmentally friendly alternative proteins, to biomanufacturing that supports long term human presence in space.

Investments that are changing the future, made possible by the Inflation Reduction Act, are likely to spur action toward combating climate change by creating thousands of clean manufacturing jobs to support sustainability and the transition to a circular bioeconomy. The CHIPS and Science ACT of 2022 promises to provide a wealth of monetary support for STEM education programs, research training, and the expansion of public-private partnerships that can accelerate workforce development through collaborations and shared resources.

President Biden's Executive Order describes policies which shall be collectively referred to as the National Biotechnology and Biomanufacturing Initiative.

The Order states that it is the policy of the Administration to:

- bolster and coordinate Federal investment in key research and development (R&D) areas of biotechnology and biomanufacturing in order to further societal goals;
- foster a biological data ecosystem that advances biotechnology and biomanufacturing innovation, while adhering to principles of security, privacy, and responsible conduct of research;
- improve and expand domestic biomanufacturing production capacity and processes, while also increasing piloting and prototyping efforts in biotechnology and biomanufacturing to accelerate the translation of basic research results into practice;
- boost sustainable biomass production and create climate-smart incentives for American agricultural producers and forest landowners;
- expand market opportunities for bioenergy and biobased products and services;
- train and support a diverse, skilled workforce and a next generation of leaders from diverse groups to advance biotechnology and biomanufacturing
- clarify and streamline regulations in service of a science- and risk-based, predictable, efficient, and transparent system to support the safe use of products of biotechnology
- promote standards, establish metrics, and develop systems to grow and assess the state of the bioeconomy; to better inform policy, decision-making, and investments in the bioeconomy; and to ensure equitable and ethical development of the bioeconomy
- secure and protect the United States bioeconomy by adopting a forward-looking, proactive approach to assessing and anticipating threats, risks, and potential vulnerabilities (including digital intrusion, manipulation, and exfiltration efforts by foreign adversaries), and by partnering with the private sector and other relevant stakeholders to jointly mitigate risks to protect technology leadership and economic competitiveness

- engage the international community to enhance biotechnology R&D cooperation in a way that is consistent with United States principles and values and that promotes best practices for safe and secure biotechnology and biomanufacturing research, innovation, and product development and use
- elevate biological risk management as a cornerstone of the life cycle of biotechnology and biomanufacturing R&D, including by providing for research and investment in applied biosafety and biosecurity innovation[79]

Critical to capitalizing on these legislative policies and investments is the need to build public awareness of career opportunities in fields like synthetic biology and bioprocess engineering. Early exposure to these types of careers through family engagement, out-of-school and summer experiences, internships, career talks, mentoring with industry professionals and can provide on-ramps into the bioindustrial manufacturing workforce.

However, the accelerated pace of technological innovation in biomanufacturing brings with it the urgent need for interdisciplinary training, as well as the need to develop robust biosecurity systems and cybersecurity infrastructure to protect society from misuse, bad actors, and threats to national security. Moving forward, ethical considerations about the unintended consequences of innovations will be essential. Key take aways from this scan include the need to emphasize a balance between the opportunities for innovation with the reality of potential risks.

References

1. National Academies of Sciences, Engineering, and Medicine. (2020). Safeguarding the Bioeconomy. Washington, DC: The National Academies Press. https://doi.org/10.17226/25525
2. Sanders, R. (October 20, 2020). $275 million commitment to brew better molecules for manufacturing. Berkeley News. https://news.berkeley.edu/2020/10/20/275-million-commitment-to-brew-better-molecules-for-manufacturing
3. BioMADE. (2022). "About BioMADE." BioMADE, August 13, 2022. https://www.biomade.org/about-biomade
4. Aguilar, F. (1967). Scanning the Business Environment. New York: Macmillan Scanning the Environment: PESTEL Analysis.
5. de Bruin, L. (September 18, 2016). Scanning the Environment: PESTEL Analysis. Business-to-You. https://www.business-to-you.com/scanning-the-environment-pestel-analysis/
6. Ziker, C., Johnson, J., & Paredes, P. (2022). STEMconnector & BioMADE Innovation Lab Brief: Exploring the Bioindustrial Manufacturing Workforce Opportunities, Challenges and Emerging Trends, Manhattan Beach, CA, STEMconnector
7. Igini, M. (August 17, 2022). All You Need to Know About The US Inflation Reduction Act. Policy and Economics, Earth.org. https://earth.org/inflation-reduction-act/
8. Anthony Blinken, Secretary of State. (February 19, 2022). The United States Officially Rejoins the Paris Agreement. U.S. Department of State. https://www.state.gov/the-united-states-officially-rejoins-the-paris-agreement/
9. U.S. Department of State, (April 23, 2021). Leaders Summit on Climate. https://www.state.gov/leaders-summit-on-climate/about/
10. Esposito, D. (August 23, 2022). Inflation Reduction Act Benefits: Clean Energy Tax Credits Could Double Deployment. Forbes. https://www.forbes.com/sites/energyinnovation/2022/08/23/inflation-reduction-act-benefits-clean-energy-tax-credits-could-double-deployment/?sh=3e1124126727
11. The House of Representatives Committee on Science, Space, and Technology. (2022). "Ensuring the U.S. is Equipped to Lead in Science and Innovation." Learn More About the CHIPS and Science Act. August 13, 2022. https://science.house.gov/chipsandscienceact
12. United Nations. Sustainability Development Goals. https://www.un.org/sustainabledevelopment/climate-
13. Farber, D. (July 28, 2022). Climate Adaptation Moves Toward Center Stage. Legal Planet, Berkeley Law UCLA Law. https://legal-planet.org/2022/07/28/climate-adaptation-moves-toward-center-stage/
14. Government Finance Officers Association of the United States and Canada, (2022). The Infrastructure and Jobs Act (IIJA) Implementation Resources. https://www.gfoa.org/the-infrastructure-investment-and-jobs-act-iija-was
15. Olszak, R. (March 24, 2022). Ukraine War Triggers New Supply Chain Threats & Challenges, RGP. https://rgp.com/insights/ukraine-war-supply-chain-threats/
16. The White House Briefing Room, (2022). Fact Sheet: CHIPS and Science Act Will Lower Costs, Create Jobs, Strengthen Supply Chains, and Counter China, (August 9, 2022). Statements and Releases. https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/

17. BioMADE. (2022). “DoD Approves $87 Million for Newest Bioindustrial Manufacturing Innovation Institute.” BioMADE, August 13, 2022. https://www.biomade.org/news/dod-approves-87-million-for-newest-bioindustrial-manufacturing-innovation-institute

18. National Science Foundation, (2022). National Science Foundation announces $8.6 million partnership with leading foundations to improve U.S. STEM education, July 6, 2022. https://www.nsf.gov/news/special_reports/announcements/070622.jsp

19. Degnarain, N. (May5, 2020). Could Biomanufacturing See A Renaissance In The Post-Covid Economy? Forbes.com. https://www.forbes.com/sites/nishandegnarain/2020/05/05/could-biomanufacturing-see-an-economic-renaissance-in-the-post-covid-economy/?sh=5f2cbd2c5b02

20. Hinman, A. and Friedman D. (2022). Actions to Enable an Equitable and Innovative U.S. Bioeconomy: Creating Equitable Biotechnology Innovation Regions throughout the United States. Engineering Biology Research Consortium, ebrc.org/publications, doi.org/10.25498/E4X59D. https://ebrc.org/wp-content/uploads/2022/05/Actions-to-Enable-an-Equitable-and-Innovative-U.S.-Bioeconomy.pdf

21. Hannon, M., Gimpel, J., Tran, M., Rasala, B., Mayfield, S. (2010). Biofuels from algae: challenges and potential. Biofuels. 2010 Sep;1(5):763-784. https://pubmed.ncbi.nlm.nih.gov/21833344/

22. Lee, K. (January 14, 2020). Mind The Gap Bridging the ‘Valley of Death’ for U.S. Biomanufacturing, National Institute of Standards and Technology, U.S. Department of Commerce. https://www.nist.gov/blogs/taking-measure/mind-gap-bridging-valley-death-us-biomanufacturing

23. Richard, T. (2010). “Challenges in Scaling Up Biofuels Infrastructure” Science Vol 329, Issue 599 (2010): 793-796. https://www.science.org/doi/10.1126/science.1189139

24. Freethink.com (2022). Synthetic Biology for Climate Change. Ginkgo Bioworks. https://www.freethink.com/science/synthetic-biology-for-climate-change

25. Gerage, A. (2020), Accelerating Biological Systems Design for Sustainable Biomanufacturing; A new cell-free platform rapidly identifies optimal enzymes for sustainable fuels and materials. Northwestern University. https://www.mccormick.northwestern.edu/news/articles/2020/06/accelerating-biological-systems-design-for-sustainable-biomanufacturing.html

26. LabCentral. (2022). What is LabCentral. https://labcentral.org/about/what-is-labcentral/

27. Fegen., A. (August 9, 2022). CHIPS and Science Act Authorizes Significant Investment in STEM. Association of Science and Technology Centers. https://www.astc.org/issues-policy-and-advocacy/chips-and-science-act-authorizes-significant-investment-in-stem/

28. Miller, K., Sonnert, G., & Sadler, P. (2018). The Influence of Students’ Participation in STEM Competitions on Their Interest in STEM Careers. International Journal of Science Education, Part B: Communication and Public Engagement, 8(2), 95–114. https://doi.org/10.1080/21548455.2017.1397298

29. Mitchell, R., Dori, Y., & Kuldell, N. (2011). Experiential Engineering Through iGEM—An Undergraduate Summer Competition in Synthetic Biology. Journal of Science Education and Technology, 20, 156–160. https://doi.org/10.1007/s10956-010-9242-7

30. International Genetically Engineered Machine Competition (2022). https://www.igem.org/press/kit

31. Patel, M., Santhanam, N., & Tandon, S. (2013). Exploring SynBio’s potential for semicondutor players. McKinsey & Company, Inc. https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/semiconductors/issue%203%20autumn%202013/pdfs/9_syntheticbiology.pdf#:~:text=Exploring%20SynBio%E2%80%99s%20potential%20for%20semiconductor%20players%20The%20disruptive,first%20transistor%20in%20the%20era%20of%20vacuum%20tubes

32. Rahman, A., Putman, R., Hengge, N., & Miller, C. (2017). Biomanufacturing through iGEM-An International Student Competition. Biological Engineering Faculty Publications, 1–17. https://digitalcommons.usu.edu/bioeng_facpub/147/

33. Biomanufacturing Training and Education Center. (2022). https://www.btec.ncsu.edu/

34. Schron, C. (March 25, 2021). Extended Reality Technologies in Manufacturing Training. Tooing U-SME. https://www.toolingu.com/Resources/Blog/March-2021/xr-technologies-in-manufacturing-training

35. Dreamscape Learn. (2020). Dreamscape Learn to transform educational experience through exploration. Arizona State University News. https://news.asu.edu/2020-09-18-discoveries-dreamscape-immersive-asu-partnership-virtual-reality-learners-worldwide https://www.dreamscapelearn.com/

36. Lund., S., Madgavkar, A., Manyika, J., Smit.,S., Ellingrud, K., Meaney, M., & Robinson, O. (2021). The future of work after COVID-19. McKinsey Global Institute. https://www.mckinsey.com/featured-insights/future-of-work/the-future-of-work-after-covid-19

37. Bioscience Core Skills Institute. (2022). https://www.coreskillsinstitute.com/

38. Schultz, E. (2022). The Fourth Industrial Revolution, YouTube, CNBC International, Davos Switzerland. https://video.search.yahoo.com/search/video?fr=mcafee&ei=UTF-8&p=google+the+third+industrial+revolution&type=E210US105G91647#id=4&vid=cec94f3883cf0dc4d80fcd1ae91619da&action=view

39. Meyers, S., & Cunningham, C. (December 14, 2021). Understanding the Impacts of Industry 4.0 on Manufacturing Organizations and Workers. Smart Factory, University of Tennessee, Chattanooga.

40. Chui, M., Evers, M., Manyika, J., Zheng, A., & Nisbet, T. (May, 2020). The Bio Revolution: Innovations Transforming Economies, Societies, and Our Lives". McKinsey. https://www.mckinsey.com/industries/life-sciences/our-insights/the-bio-revolution-innovations-transforming-economies-societies-and-our-lives

41. National Science Foundation Future Manufacturing (FM). (2022). Synopsis. https://beta.nsf.gov/funding/opportunities/future-manufacturing-fm

42. Wintle, B.C., Boehm, C.R., Rhodes, C., Molloy, J.C., Millett, P., Adam, L., Breitling, R., Carlson, R., Casagrande, R., Dando, M.R., Doubleday, R., Drexler, E., Edwards, B., Ellis, T., Evans, N.G., Hammond, R., Haseloff, J., Kahl, L., Kuiken, T., Lichman, B.R., Matthewman, C.A., Napier, J.A., ÓhÉigeartaigh, S.S., Patron, N.J., Perello, E., Shapira, P., Tait, J., Takano, E., & Sutherland, W.J. (2017). A transatlantic perspective on 20 emerging issues in biological engineering. eLife, 6. https://www.semanticscholar.org/paper/A-transatlantic-perspective-on-20-emerging-issues-Wintle-Boehm/4636a4b30c04c11bccf8cd449921f781beddec14

43. Gingko Bioworks. (2017). Accelerating Automation in Organism Design. https://www.ginkgobioworks.com/ginkgo-transcriptic/

44. Donohoue, P.D., Barrangou, R., May, A.P. (2018). Advances in Industrial Biotechnology Using CRISPR-Cas Systems. Trends Biotechnol. 2018 Feb;36(2):134-146. doi: 10.1016/j.tibtech.2017.07.007. Epub 2017 Aug 1. PMID: 28778606. https://pubmed.ncbi.nlm.nih.gov/28778606/

45. Gronvall, G.K. (2019). Synthetic Biology: Biosecurity and Biosafety Implications. In: Singh, S., Kuhn, J. (eds) Defense Against Biological Attacks. Springer, Cham. https://doi.org/10.1007/978-3-030-03053-7_11. https://link.springer.com/chapter/10.1007/978-3-030-03053-7_11

46. Klamm, L. (March 12, 2021) Bio-cybersecurity discussion series to cover threats to synthetic biology, biomanufacturing, and bio-data. https://source.colostate.edu/bio-cybersecurity-discussion-series-to-cover-threats-to-synthetic-biology-biomanufacturing-and-bio-data/

47. Built with Biology Podcast. (2022). Fiona Mischel speaks with James Diggans, Head of Biosecurity at Twist Bioscience. Built With Biology Podcast: Why Should Everyone Care About Biosecurity? https://www.twistbioscience.com/resources/webinar/built-biology-podcast-why-should-everyone-care-about-biosecurity

48. Twist Bioscience. (2022). Unleash the Power of the Platform. Twist Bioscience. https://www.twistbioscience.com/?utm_source=google&utm_medium=cpc&utm_campaign=PSR-GLBL-FY21-1808-MULTI-Branded&adgroup=114820227303&utm_term=twist%20biosciences&utm_content=kwd-386116309564&creative=491329828693&device=c&matchtype=b&location=9032179&gclid=Cj0KCQjw39uYBhCLARIsAD_SzMT_2gqv6vlQYBMvqRFcRE4sbbTvUBqJ0okq7n4PUJlaNZP3uZ7ZhJkaAjvfEALw_wcB

49. Averesch, N.J., Berliner, A.J., Nangle, S.N., Zezulka, S., Vengerova, G.L., Ho, D., Casale, C.A., Lehner, B.A., Jessica Snyder, J.E., Clark, K.B., Dartnell, L.R., Criddle, C.S., Arkin, A.P. (2022). Biomanufacturing for Space-Exploration – What to Take and When to Make. Preprints 2022, 2022070329 (doi: 10.20944/preprints202207.0329.v1). https://www.preprints.org/manuscript/202207.0329/v1

50. Berliner, A. J., Lipsky, I., Ho, D., Hilzinger, J. M., Vengerova, G., Makrygiorgos, G., ... & Arkin, A. P. (2022). Space bioprocess engineering on the horizon. Communications Engineering, 1(1), 1-8. https://www.nature.com/articles/s44172-022-00012-9

51. Fell, A. (March 19, 2022). Lettuce Could Protect Astronauts' Bones on Mars Trip. University of California Davis. https://www.ucdavis.edu/curiosity/news/lettuce-could-protect-astronauts-bones-mars-trip

52. The White House Briefing Room. (August 19, 2022). Fact Sheet: The Inflation Reduction Act Supports Workers and Families. https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/19/fact-sheet-the-inflation-reduction-act-supports-workers-and-families/

53. Palahi, M. (Oct. 6,2020). Why the world needs a 'circular bioeconomy' - for jobs, biodiversity and prosperity. Circular Economy. https://www.weforum.org/agenda/2020/01/the-world-needs-a-circular-economy-lets-make-it-happen/

54. FastCo Works. (August 29, 2022). 'Fast tech' is unsustainable: The circular economy is the smart answer for growth: Designing durable, reusable, and recyclable products helps tech companies challenge the reigh of "fast tech". FastCompany. https://www.fastcompany.com/90772025/fast-tech-is-unsustainable-the-circular-economy-is-the-smart-answer-for-growth

55. Lau, W. W., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., ... & Palardy, J. E. (2020). Evaluating scenarios toward zero plastic pollution. Science, 369(6510), 1455-1461. DOI: 10.1126/science.aba947

56. Kruger, J.S., Wiatrowski M, Davis, R.E, Dong, T, Knoshaug, E.P., Nagle, N.J., Laurens L.M.L., and Pienkos, P.T. (2022. Enabling Production of Algal Biofuels by Techno-Economic Optimization of Product Suites. Front. Chem. Eng. 3:803513. doi: 10.3389/fceng.2021.803513

57. Richards, E. (July 9, 2022). Careers in Biofuels: Green Jobs Biofuels. Bureau of Labor Statistics. https://www.bls.gov/green/biofuels/biofuels.pdf

58. International Energy Agency, (2022). Bioenergy. https://www.iea.org/fuels-and-technologies/bioenergy

59. FastCo Works. (August 29, 2022). 'Fast tech' is unsustainable: The circular economy is the smart answer for growth: Designing durable, reusable, and recyclable products helps tech companies challenge the reigh of "fast tech". FastCompany. https://www.fastcompany.com/90772025/fast-tech-is-unsustainable-the-circular-economy-is-the-smart-answer-for-growth

60. Gillispie, M. (August 13, 2022). Billions pour into bioplastics as markets expand, with Cargill major player. Star Tribune. https://www.startribune.com/billions-pour-into-bioplastics-as-markets-expand-with-cargill-major-player/600198053/

61. Kircher M. (2022) Economic Trends in the Transition into a Circular Bioeconomy. Journal of Risk and Financial Management. 2022; 15(2):44. https://doi.org/10.3390/jrfm15020044

62. Xu, X., Sharma, P., Shu, S. et al. (2021). Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nat Food 2, 724–732. https://doi.org/10.1038/s43016-021-00358-x

63. Good Food Institute. (2022). Cultivated Meat. https://gfi.org/cultivated/

64. Smith, A. & Shah, S. (2021). "The Government Needs an Innovation Policy for Alternative Meats." Issues in Science and Technology (February, 18, 2021). https://issues.org/alternative-meat-innovation-environment-animals/

65. Kahn, J. (April 7, 2021). Company on a quest for "kosher bacon" raises $24 million for its lab-grown fat. Fortune.com https://fortune.com/2021/04/07/kosher-bacon-mission-barns-lab-grown-fat-fundraising/

66. Solvieva, D. (March 18, 2020). Will the future of meat be animal, vegetable, or lab-born? https://fortune.com/2020/03/18/future-of-meat/

67. Bartoe, M.S. (2022). Market Trends in Growing Plant-based Meat Category. Sensient Food Colors. https://sensientfoodcolors.com/en-us/industry-trends/market-trends-growing-plant-based-meat-category/

68. Impossible Foods. (2022). Impossible Foods, Inc. https://impossiblefoods.com/

69. Plant Based Food Association. (April 6, 2022). Plant based food retail sales grow 27% to $7 billion in 2020. Plant Based Food Association. News Release: Plant-based food retail sales grow 27% to $7 billion in 2020. Plant Based Food Association. https://www.plantbasedfoods.org/2020-retail-sales-data-announcement/#:~:text=WASHINGTON%20%E2%80%94%20New%20data%20released%20today%20by%20the,the%20total%20plant-based%20market%20value%20to%20%247%20billion

70. Hannon, M., Gimpel, J., Tran, M., Rasala, B., Mayfield, S. (2010). Biofuels from algae: challenges and potential. Biofuels. 2010 Sep;1(5):763-784. https://pubmed.ncbi.nlm.nih.gov/21833344/

71. Shapira, P., Matthews, N., Cizauskas, C.A., Aurand, E.R., Friedman, D.C., Layton, D.S., Maxon, M.E., Palmer, M.G., & Stamford, L. (2022). "Building a Bottom-Up Bioeconomy." Issues in Science and Technology 38, no. 3 (Spring 2022): 78–83. https://issues.org/building-bioeconomy-engineering-biology-shapira/

72. Richards, T.,(2010). "Challenges in Scaling Up Biofuels Infrastructure." Science Vol 329, Issue 5993 (Aug 2010): 793-796. https://www.science.org/doi/10.1126/science.1189139

73. Bryant, C., Szejda, K., Parekh, N., Deshpande, V., & Tse, B. (2019). A Survey of Consumer Perceptions of Plant-Based and Clean Meat in the USA, India, and China. Frontiers in Sustainable Food Systems, 3. https://www.frontiersin.org/articles/10.3389/fsufs.2019.00011

74. Klieng, N. (2021). Shell outlines plan for sustainable jet fuel, UpStream. https://www.upstreamonline.com/energy-transition/shell-outlines-plan-for-sustainable-jet-fuel/2-1-1071121

75. Schmidt Futures. (2022). The US Bioeconomy: Charting a Course for a Resilient and Competitive Future - a Bioeconomy Strategy. https://www.schmidtfutures.com/wp-content/uploads/2022/04/Bioeconomy-Task-Force-Strategy-4.14.22.pdf

76. Stone, A. (2022). Enhancing Risk Management in the Defense Department.C4ISRNET, SPLUNK. https://www.splunk.com/en_us/form/enhancing-risk-management-in-the-defense-department.html

77. National Institutes for Standards and Technology. (2022). NIST Cybersecurity Framework. https://www.nist.gov/cyberframework

78. Wilkinson, M. D. et al. (2016). The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data, 3, 160018. https://doi.org/10.1038/sdata.2016.18

79. The White House Briefing Room. (September 12, 2022). Executive Order on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure Bioeconomy. https://www.whitehouse.gov/briefing-room/presidential-actions/2022/09/12/executive-order-on-advancing-biotechnology-and-biomanufacturing-innovation-for-a-sustainable-safe-and-secure-american-bioeconomy/

Appendix

Table 1. K-16 Programs that Build Awareness and Capacity in Bioindustrial Manufacturing

K-12 Programs	Program Description	Link to Website
Engineering is Elementary (EIE)	EIE promotes problem solving skills, offers videos, lesson plans, professional development for teachers, and at-home activities for families.	https://www.eie.org/stem-curricula/engineering-grades-prek-8/engineering-is-elementary
Project Lead the Way (PLTW)	Project Lead the Way's Gateway program offers eighth grade students' exposure to engineering through robotics, electronics, and engineering skills that are foundational to bioindustrial manufacturing.	https://www.pltw.org/our-programs/pltw-gateway
Ilumina Foundation	Illumina provides genomics literacy resources for students and educators that teach them about DNA sequencing and connect them to careers.	www.Illumina.com/stem
BioBuilder	BioBuilder offers in-person training in synthetic biology at Learning Labs for students and teachers; provides online resources for teachers and hands-on kits for students; and provides in-person trainings for professionals seeking to advance their synthetic biology skills.	https://biobuilder.org/
Bay Area BioScience Education Community	Bay Area BioScience Education Community delivers lab materials to teachers and districts here in the South San Francisco community.	https://babec.org/
Amgen Biotech Experience (ABE)	Amgen offers an innovative science education program that provides teachers with professional development and education materials and loans research-grade equipment to high schools in 13 countries at no cost.	https://www.amgenfoundation.org/science-education/amgen-biotech-experience
Algae Foundation	Algae Foundation is a partnership between academic institutions, national research laboratories, and industry leaders, the consortium's goal is to develop novel educational programs to strengthen industry workforce capabilities, by focusing on the skills needed to support the commercialization of algal products. Algae Foundation also supports the Algae Academy, a STEM educational program for K-12 students.	https://algaefoundationatec.org/
Biobits	BioBits take advantage of cutting-edge freeze-dried cell-free technology to make it possible to run biological experiments without living cells. Learn about DNA and how it makes proteins by making your own fluorescent proteins and more! BioBits are portable, user-friendly, and inexpensive, making it possible to teach molecular biology outside of the lab.	https://www.mybiobits.org/
Boston University Rise Program	RISE offers two tracks for High School students. For the Internship track, students spend 40 hours each week working on research projects designed by their mentor. For the Practicum track, students conduct group research in a university setting.	https://www.bu.edu/summer/high-school-programs/rise-internship-practicum/

Army Educational Outreach Program	The Army Educational Outreach Program STEM Enrichment activities spark student interest in STEM from the earliest grades through high school. They also provide experiential learning opportunities for educators. These programs are great for students and teachers from all backgrounds and interests, and are designed to complement classroom learning and teaching by providing exciting, engaging, hands-on experiences.	https://www.usaeop.com/

K-12 Outreach and Teacher Training Resources	Program Description	Link to Website
Navy STEM Center	STEM development begins with Naval STEM outreach programs at the Pre-K through 12th grade levels, continues through undergraduate and graduate school, supports student advancement into post-doctoral work, and continues through all stages of their STEM professions.	https://www.nre.navy.mil/education-outreach/naval-stem
Bay Area BioScience Education Community	Bay Area BioScience Education Community delivers lab materials to teachers and districts here in the South San Francisco community.	https://babec.org/
BioBuilder	BioBuilder offers in-person training in synthetic biology at Learning Labs for students and teachers; provides online resources for teachers and hands-on kits for students; and provides in-person trainings for professionals seeking to advance their synthetic biology skills.	https://biobuilder.org/
BioTech SYSTEM	BioTech SYSTEM is a K-14 STEM education consortium administered by the UC Davis Biotechnology Program in collaboration with regional colleges and universities, community organizations, local governments, school districts and industry partners. The overarching goal of BioTech SYSTEM is raising awareness of biotech career paths, supporting students and teachers in experiential learning opportunities and improving public science literacy. Flagship activities of the BioTech SYSTEM are Train-the-Trainer Workshops for biotech educators, the Teen Biotech Challenge poster competition for middle and high school students and the SPARK Summer Research Program for high school students.	https://biotech.ucdavis.edu/biotech-system

Science Competitions	Program Description	Link to Website
International Genetically Engineered Machine Competition (IGEM)	The iGEM Competition is an annual, worldwide synthetic biology event aimed at undergraduate university students, as well as high school and graduate students. The iGEM Competition gives students the opportunity to push the boundaries of synthetic biology by tackling everyday issues facing the world. Multidisciplinary teams work together to design, build, test, and measure a system of their own design using interchangeable biological parts and standard molecular biology techniques.	https://igem.org/

Teen Biotech Challenge	The Teen Biotech Challenge 2023 is an online poster design competition for Grades 6-12 that allows students to demonstrate research skills, scientific communication skills, and creativity. Participating students will be asked to submit a poster (.pdf) for judging in one of the following biotech-related research categories: Agricultural Biotechnology; Biomanufacturing; Computational Biology and Genomics; Environmental Biotechnology and Planetary Health; Molecular Tools: Nanobiotechnology, Synthetic Biology and Genetic Engineering; and, Regenerative Medicine and Biomedical Engineering.	https://biotech.ucdavis.edu/teen-biotech-challenge
Junior Science and Humanities Symposium	JSHS is an annual symposium, competition, and year-round digital programming funded by the Department of Defense (DoD), and administered by the National Science Teaching Association (NSTA). It provides mentoring, scholarship, and career pathways for young minds from everywhere to find success, growth, and connection in STEM.	https://jshs.org/
The Regeneron International Science and Engineering Fair (Regeneron ISEF)	The Regeneron International Science and Engineering Fair (ISEF) is the world's largest international pre-college science competition. It is owned and administered by the Society for Science.	https://www.societyforscience.org/isef/
USA Science and Engineering Festival	The mission of the USA Science & Engineering Festival is to stimulate and sustain the interest of our nation's youth in STEM by producing and presenting compelling, exciting, and educational STEM events and programs.	https://usasciencefestival.org/

High School/ Community College	Program Description	Link to Website
Austin Community College	ACC offers Dual Credit Biotechnology courses, Early College High School, and Internships (both formal and informal) Informal internship experiences, where students are closely supervised under a mentor and apply their entry level knowledge and training in a bioscience laboratory. The experience may be internal to the college where the student works on independent projects, or external to the college, where the student is mentored and supervised by a workplace employee. This may be a paid or unpaid experience.	http://www6.austincc.edu/schedule/index.php?op=browse&opclass=ViewSched&term=222F000&disciplineid=PCBIT&yr=2023&ct=CC
Skyline College	Skyline College's Biotechnology Manufacturing Technician Associate in Science Degree Program prepares graduates with the skills and experience to work in the biotechnology industry as a production technician. Students will culture and maintain bacteria, yeast, and mammalian cells as well as gain experience in the recovery of proteins that the cultures produce. Students will develop skills in good manufacturing practices (GMP) by maintaining records and following standard operating procedures.	https://catalog.skylinecollege.edu/current/programs/biotechnology-manufacturing-technician-as.php
Solano Community College	Solano Community College's Baccalaureate degree program in biomanufacturing offers a Bachelors of Science degree in Bioindustrial Manufacturing.	https://welcome.solano.edu/biomanufacturing/

Des Moines Area Community College	A DMACC Biotechnology Certificate as a part of the DMACC AS plus Certificate degree or as an addition to previous coursework and experience will assist students in finding a career in cutting edge research in this fast growing and exciting scientific frontier.	https://www.dmacc.edu/programs/biotechnology/Pages/welcome.aspx
Laney College	Laney College offers hybrid courses with in-person labs in biotechnology.	https://laneybiotech.com/
Ohloni College	Ohloni College offers programs in biotechnology, including a Certificate of Achievement in Biomanufacturing and an Associates degree in Biotechnology.	https://www.ohlone.edu/biotech
Shoreline Community College	Shoreline Community College allows students to gain the skills to manufacture vaccines and other therapeutic products in the growing biotechnology industry in just 10 weeks, without a degree or background in science required. Paid internships may also be available after courses are completed.	https://www.shoreline.edu/programs/biotechnology/essentials-of-biomanufacturing-certificate.aspx
MiraCosta College	MiraCosta College is one of only 15 California community colleges authorized to offer a bachelor's degree program. Upper degree coursework for the biomanufacturing bachelor's degree began in fall 2017. The degree program prepares students for work within the biotechnology industry in the unique environment of biological production where science thrives in partnership with quality and compliance.	https://www.miracosta.edu/academics/degree-and-certificate-programs/math-and-sciences/biotechnology/biomanufacturing-bachelors-degree/index.html
Bioscience Core Skills Institute (BCSI)	Bioscience Core Skills Institute (BCSI) provides workforce skills assessment and digital micro-credentialing that are valid, reliable, and trusted by the bioscience industry. Working with educational and industry partners, BCSI provides assessment opportunities and documentation of skills.	https://www.coreskillsinstitute.com/credentials

Internships/ Apprentice Programs	Program Description	Link to Website
Navy Science and Engineering Apprentice Program	SEAP is an 8-week high school apprenticeship opportunity at one of nearly 25 naval laboratories or warfare centers. Accepted students gain real-world, hands-on experience and research skills while being introduced to the Navy and Marine Corps science and technology environment.	https://navalsteminterns.us/seap/
ASU Biosense Network	The BioSense Network is a collaboration between ASU's Biodesign Institute and ASU's Mary Lou Fulton Teachers College, supported by funding from the National Defense Education Program. The purpose of this network is to build a community of educators who can guide middle and high school students in sense-making around biotechnology concepts and applications. Students who are 16 years or older will be offered hands-on summer research experiences at ASU and Defense laboratories during Summer 2022. Teachers will receive certification from Mary Fulton Teachers College as well as a stipend for their involvement.	https://www.biosense.network/

Science Undergraduate Laboratory Internship at National Labs	Science Undergraduate Laboratory Internship at National Labs encourages undergraduate students and recent graduates to pursue STEM careers by providing research experiences at the Department of Energy (DOE) laboratories. Selected students participate as interns appointed at one of 17 participating DOE laboratories/facilities. They perform research, under the guidance of laboratory staff scientists or engineers, on projects supporting the DOE mission.	https://science.osti.gov/wdts/suli/How-to-Apply/Selecting-a-Host-DOE-Laboratory
University of California Davis	Biotechnology at UC Davis offers new ways of production using biological materials, organisms, and systems. Leading research in this area enables the synthesis of pharmaceuticals, biodegradable polymers, renewable fuels, and other bio-based products from diverse feedstocks. UC Davis faculty are developing new crops for improved disease and pest resistance and adaptation to changing climate and conditions.	https://bae.ucdavis.edu/research-areas/biotechnical-engineering
UC Davis Biochemical Engineering Major	The undergraduate major in Biochemical Engineering is a four-year program that culminates in students receiving a Bachelor of Sciences Degree (BSc). This program is one of the few in the country that is an ABET (Accreditation Board of Engineering and Technology; see abet.org) accredited undergraduate engineering degree in Biochemical Engineering. In the first two years, students take foundational courses in chemistry, biology, microbiology, mathematics and physics and in the upper division they take courses in process engineering (material balances, fluid mechanics, heat transfer, mass transfer, thermodynamics, kinetics and reaction engineering, process modelling and control, and engineering economics) along with specialized courses in bioprocess engineering (bioreactor design and analysis, bioseparations, bioprocess engineering laboratory, biotech facility design and regulatory compliance) culminating in a capstone design project focused on design and techno-economic modelling and analysis of a biomanufacturing facility in collaboration with industrial or academic partners.	https://che.engineering.ucdavis.edu/undergraduate/prospective-students/biochemical-engineering-major
UC Davis Biotechnology Major	The UC Davis undergraduate major in Biotechnology is a four-year program that culminates in students receiving a Bachelor of Sciences Degree (BSc). In the first two years, students develop a strong and general background in the biological sciences with an emphasis on the basic principles of genetics, molecular biology, cell biology and recombinant DNA. In their third and fourth year, students focus their studies into one of four general areas for more in depth studies: microbial biotechnology, animal biotechnology, plant biotechnology, or bioinformatics. Students are required to complete an upper division internship for the major.	https://biotechmajor.sf.ucdavis.edu/

UC Davis Designated Emphasis in Biotechnology	The DEB is an inter-graduate group program that allows Ph.D. students to receive and be credited for training in the area of biotechnology. The program brings together students and faculty from across 29 STEM disciplines to create an educational ecosystem that promotes collaborative team science, effective science communication for diverse audiences, and an entrepreneurial mindset for tackling complex global challenges across human health, agriculture and the environment. Through required coursework and seminars, DEB students are introduced to a range of biotechnology research areas with focus on the intersection of molecular biology and engineering in the development of biomanufacturing platforms for industrial enzymes, therapeutics, biofuels and other high value products. The cornerstone of the DEB training environment is a required 3–6-month professional internship, which usually takes place in a biotechnology industry setting.	https://deb.ucdavis.edu/
UC Berkeley	UC Berkeley's Master of Bioprocess Engineering (MBPE) degree program is driven by the increasingly important role of the bioprocessing field in the world economy. It is designed for the incoming student who possesses the interest and aptitude but not yet the hands-on experience to step into a bioprocessing role. The MBPE program bridges this expertise and experience gap for those who wish to pursue careers as Associate Scientists or Bioprocess Engineers in the bioprocessing field to design, develop, and implement real-time solutions and strategies.	https://chemistry.berkeley.edu/grad/cbe/bioprocess-
Boston University STEM Pathways	The main objective of STEM Pathways is to inspire, mentor, train, and empower current and future generations of students, with a focus on underrepresented groups. Through STEM Pathways, students will be able to: obtain academic and research experiences in the growing field of Synthetic Biology; pursue rewarding careers in computer and biomedical engineering; and influence innovations and impacts in STEM, community education, and outreach.	https://www.stempathways.org/research
DoD SMART Program	The Department of Defense (DoD) Science, Mathematics, and Research for Transformation (SMART) Program is a Science, Technology, Engineering, and Mathematics (STEM) focused scholarship-for-service program.	http://www.smartscholarship.org

Other Resources	Program Description	Link to Website
InnovATEBIO	The InnovATEBIO National Biotechnology Education Center is working to advance the education of highly skilled technicians for the nation's biotechnology workforce. Toward this goal, InnovATEBIO is providing leadership in biotechnology technician education, including support for development and sharing of best practices and emerging technologies in biotechnology workforce development.	https://innovatebio.org/
The Golden LEAF Biomanufacturing Training and Education Center (BTEC)	BTEC works with industry to design and develop a number of open-enrollment courses that enhance the knowledge and skills of biotechnology and biomanufacturing professionals. BTEC offers several options to expand the process expertise of individuals and the industry, including professional development courses, seminars, and customized courses.	https://www.btec.ncsu.edu/industry/

Table 2. **Insights gathered by STEMconnector facilitators during table discussions at the STEMconnector BioMADE Innovavation Lab in July, 2022.**

Participants identified gaps regarding a lack of awareness, skills, opportunities, lack of high quality programming.

Lack of awareness that manufacturing jobs exist.
Technical form of biomanufacturing is not as well known; however, people are more aware of classical manufacturing.
Blue collar manufacturing is more of the face of “manufacturing.” U.S. does not consider manufacturing as much.
Local perception/attitude.
No one teaches CTMP and students are unprepared for industrial biology.
People aren’t prepared for biology (industrial and production).
Students are unaware of the pathway available to them.
Students do not know where to go to get there for necessary training.
There is a lack of understanding with those advising students and a lack of conventional wisdom.
There is a need for dual enrollment programs.
Students do not know people within the field of Bioindustrial Manufacturing.
Biotech is not a part of the culture.
We are not tapping into the vo-tech students.
Need to develop awareness, skills gaps, and access to opportunities.
Need for a biotechnology community of practice.
There is a lack of proliferation of high-quality programs and evidence - need to send students to high quality programs like exemplary programs at Solano, Skyline Community Colleges and models like University of Texas Austin.
There is a need for 3-4 hubs around the nation - must scale up access to programming.
Need to develop mechanisms to support and encourage stakeholder collaboration.
Cultural awareness of biotech and biomanufacturing like the awareness of what heavy manufacturing is - reduce the perception that the skills and knowledge levels of biotech and biomanufacturing are too hard or sustainable.
Demystify the relevant skills and knowledge that people already have.

How can academic institutions deepen connections with industry?

Offer real world problem solving engagement activities facilitated by industry.
Engage industry as mentors/speakers.
Create institutional partnerships that have ROI.
MOUs with industry partners and institutions (not agreements) - seek longer term engagements.
Create opportunities for feedback loops.
R & D partnerships
Real world problem engagement
Exchange opportunities
Ignited Education

Table 3. Examples of plant-based food companies that are changing the food industry and improving the environment.

Joywell Foods	Joywell Foods has developed a fermentation process that produces sweet proteins, which mimic the taste of sugar without the adverse health effects.	https://www.joywellfoods.com/
Superbrewed Foods	Superbrewed Food is a nutrition and health company focused on the development of natural ingredients based on a cultured fermentation alternative protein platform.	https://www.superbrewedfood.com/
Impossible Foods	Impossible Foods makes meat, dairy, and fish from plants, with a mission to make the global food system sustainable by eliminating the need to make food from animals.	https://impossiblefoods.com/products
Mission Barns	Mission Barns' focus is fat, which it creates from stem cell lines harvested from ducks, pigs, chickens, and cows.	https://missionbarns.com/
Motif Foods	Motif sells two ingredients: "hemami," which mimics the taste and smell of meat, and another called "appetex," which gives plant-based food a texture similar to animal tissue. These ingredients are in Motif's new food products (Gardizy, 2022).	https://madewithmotif.com/approach/

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Joseph Oleniczak	Adjunct Professor - Dual Enrollment Biotechnology	Austin Community College
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Corin Slown, Ph.D.	Associate Professor, Science Edication	California State University, Monterey Bay
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Zachary Dollar	Senior Director, Corporate & Foundation Relations	Museum Of Science - Boston
Gary Gilleskie, Ph.D.	Executive Director	North Carolina State University - Biomanufacturing Training and Education Center

Nick Kapp, Ph.D.	Research and Instructor. Biotechnology, Biomanufacturing, Microbiology, Cell and Molecular Biology. Research on development of inexpensive tools for Biochemistry and Molecular Biology.	Skyline College
Jing Folsom, Ph.D.	Associate Professor of Biology/Biotechnology	Skyline College
Leslie Igtanloc	Student	Skyline College
Jonathan Smiley	Student	Skyline College
Jim DeKloe, Ph.D.	Professor of Biological Sciences and Biotechnology, serves as the director and founder of the Industrial Biotechnology program	Solano Community College
Iralyn Eleazar	Student	Solano Community College
Ruhpreet Bains	Student	Solano Community College
Mike Silva	Staff	Solano Community College
Louise Bedsworth, Ph.D.	Executive Director at the Center for Law, Energy, and the Environment	University of California - Berkeley
Karen McDonald, Ph.D.	Distinguished Professor of Chemical Engineering.	University of California - Davis
Norbert Reich	Distinguished Professor	University Of California - Santa Barbara
Annica Wayman, Ph.D.	Associate Dean for Shady Grove Affairs. Natural and Mathematical Sciences.	University of Maryland, Baltimore County
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Arlene Bautista	Student Participant	Skyline College
Carla Grandy, Ph.D.	Interim Vice President of Instruction	College of San Mateo
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Karen McDonald, Ph.D.	Distinguished Professor of Chemical Engineering	University of California, Davis
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Kylie Messier	Manager, Events and Marketing Programs	STEMconnector
Leah McGlauchlin	Director, Bay Area Entrepreneur Center	Skyline College
Leslie Igtanloc	Student Participant	Skyline College

Nick Kapp, Ph.D.	Research and Instructor. Biotechnology, Biomanufacturing, Microbiology, Cell and Molecular Biology. Research on development of inexpensive tools for Biochemistry and Molecular Biology.	Skyline College
Paul Paredes	Researcher	Ziker Research / STEMconnector
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