The Bioeconomy & Circular Economy in Southern Arizona: Profile, Economic Baseline, & Prospects

Making Action Possible in Southern Arizona (MAP Dashboard)
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Executive Summary

Population growth, climate change, and urbanization present significant challenges for economies with limited natural resources. Governments around the world, at all levels, are developing strategies for more efficient and more sustainable resource use.

One such strategy proposed in recent years is to foster and grow the ***bioeconomy***, by embracing technological advancements (both within biological sciences as well as engineering, computing, and information sciences) and transitioning towards a more biology-based economy through the use of renewable biological materials (plant and animal products, wood, manure, food waste, algae) for inputs and energy.

Another strategy proposes to transition away from a linear ***take-make-use-dispose*** paradigm towards a ***circular economy*** that optimizes the use of energy, materials, and other resources and minimizes waste through reuse, sharing, repairing, refurbishing, remanufacturing, and recycling.

While there is significant interest in growing these areas of the economy, monitoring progress toward that goal requires establishing a baseline. This study defines the bioeconomy and circular economy within Southern Arizona (Cochise, Pima, Santa Cruz, and Yuma counties) and establishes a baseline for each by assessing the size, composition, and total contributions, including multiplier effects, to the greater Southern Arizona economy. The baseline year is 2019, the last full year before the COVID-19 pandemic when many economic relationships were affected and are not necessarily representative of "business as usual." The study also presents the economic contributions of the bioeconomy and circular economy, combined.

The study also explores and identifies examples of the ***bioeconomy, circular economy,*** or ***circular bioeconomy*** in Southern Arizona through the use of case studies. These case studies illustrate ongoing efforts in Southern Arizona to shift toward more efficient resource use and/or more effective utilization of waste and byproducts. These case studies illustrate a robust innovation ecosystem supporting the bioeconomy and identify activities that occur at the intersection of the bioeconomy and circular economy. We conclude by identifying some economic development opportunities for the circular bioeconomy in Southern Arizona.

What Did the Study Find?

- There is no single, consistent conceptual definition for the ***bioeconomy***.
  - Some definitions focus more on economic activity related to the production and use of biological resources and include agricultural production and processing while others focus more on economic activity associated with scientific breakthroughs and technological advancements enabled by research, innovation, and applications of biological and life sciences.

- Similarly, though there is generally agreement on the goal of the concept, there are more than 100 definitions of the ***circular economy***.

  - Some definitions focus on minimizing consumption of natural resources and maximizing use of waste and byproduct materials by any means possible (new designs, packaging, technologies) while others focus more on achieving circularity through the "4R" framework- ***reduce, reuse, repair, recycle***.

- The multi-disciplinary and inter-sectoral nature of the bioeconomy and circular economy creates challenges for monitoring and measuring economic activity.
  - In some industries, bio-based activities may be only a part of overall production. For example, soy ink or bioplastics production are parts of larger ink and plastics manufacturing. Data needed to separate out such specific biobased activities for measurement in the broader bioeconomy are often rare or non-existent.
  - Similarly, circular activities and practices can exist within individual businesses, within a given industry, or even within a cluster of industries, and can include both biological and non-biological resources. Data needed to separate circular activities (for example, the proportion of economic activity generated from the sale of byproducts or waste as inputs to the production processes of other businesses) from non-circular activities are non-existent.

- Nevertheless, measuring economic activity taking place in businesses that operate in *existing* industries can act as a useful proxy and serve as a baseline for the current scale of the bioeconomy and circular economy in Southern Arizona.
  - This study uses the North American Industry Classification System (NAICS) codes to identify which industries are included within the bioeconomy and circular economy and which are not.
  - This study, as presented in Section 2.3 of this report, defines the bioeconomy and circular economy in Southern Arizona by four and three components, respectively:
    - Bioeconomy industries are engaged in: (1) Production of Biological Resources (plants, animals, micro-organisms), (2) Processing of Biological Resources, (3) Health Biosciences, and (4) Bio-based Private Sector Research and Development.
    - Circular industries are engaged in: (1) Repair and Maintenance, (2) Reuse and Resale, and (3) Recycling and Remediation.
  - Because many NAICS codes are not granular enough or data does not exist to separate out bio-based or circular activities from larger industry sectors, there may be many industries (or activities within industries) in Southern Arizona that are engaged in both bio-based activities and/or circular activities that are not captured in this study.

Southern Arizona Bioeconomy Contributions

- In 2019, the ***bioeconomy*** was estimated to directly account for 21,400 jobs in Southern Arizona and directly contributed $1.7 billion to the Gross Regional Product (GRP) and $4.2 billion to regional sales.

- The largest component of the bioeconomy in Southern Arizona is comprised of industries involved in the production of crops and other agricultural products in the region's farms and ranches, accounting for approximately 80% of bioeconomy jobs and labor income, 75% of the value added attributed directly to the bioeconomy, and 60% of sales.

- Total bioeconomy employment is geographically concentrated in the western portion of Southern Arizona, in Yuma County, an important agricultural county in the region and state.
  - Agricultural commodities produced in Yuma County account for nearly one-third of agricultural sales in the state and 83% of agricultural sales in Southern Arizona.

- Including direct, indirect, and induced multiplier effects, **the total contribution of the bioeconomy to Southern Arizona in 2019 was more than $6.5 billion in sales.**
  - This level of sales **supported 36,400 jobs** and more than $2.0 billion in labor income (proprietors' income plus employee compensation). The **total contribution of the bioeconomy to the Southern Arizona GRP in 2019 was $2.9 billion**.

Southern Arizona Circular Economy Contributions

- In 2019, the ***circular economy*** directly contributed to the Southern Arizona economy by providing 8,700 full- and part-time jobs, contributing $584.2 million to the Gross Regional Product (GRP), and generating an estimated $792.7 million in regional sales.

- The largest component of the circular economy in Southern Arizona is comprised of industries involved in repair and maintenance activities, with a majority of employment and wages occurring within the automotive repair and maintenance industry.

- Economic activity related to the circular economy is geographically concentrated in Pima County, Southern Arizona's most populous county.

- Including direct, indirect, and induced multiplier effects, **the total contribution of the circular economy to Southern Arizona** in 2019 is **12,600 jobs**, more than $600 million in labor income, and approximately **$1.3 billion in sales**. The **total contribution of the circular economy to the Southern Arizona GRP in 2019 was nearly $0.9 billion**.

Southern Arizona Circular Bioeconomy Contributions

- Combined and including direct, indirect, and induced multiplier effects, **the total contribution of the bioeconomy and circular economy to Southern Arizona in 2019 was nearly $7.9 billion in sales**.
  - These sales supported **49,000 jobs**, more than $2.6 billion in labor income, and **nearly $3.8 billion of Southern Arizona GRP.**

Examples of the Circular Bioeconomy in Southern Arizona

- Due to data limitations, estimates are not developed for economic activity occurring at the *intersection* of the bioeconomy and circular economy (economic activities that are both biologically-based and circular).

However, Section 6 of this report highlights activities within the circular bioeconomy in Southern Arizona through the use of case studies.

- Taking place at the intersection of the bioeconomy and circular economy, there are a wide variety of research and innovative efforts occurring in Southern Arizona to achieve more efficient resource use, particularly water resources, through expansion and enhancement of a circular bioeconomy.

- Several case studies focus on innovative techniques, new technologies, or novel approaches to reduce both land and water requirements for agricultural production, many of which take place in controlled environment agricultural (CEA) systems. Others promote harnessing biological processes and utilizing technological advancements and specialized equipment to increase production of bioproducts. Yet others highlight opportunities to produce and utilize bioproducts by changing current agricultural practices.

- In many of the case studies, circularity is introduced into the bioeconomy through the use of waste streams and/or byproducts for productive uses.

- While some of the case studies rely on technological advancements and patented and patent-pending applications, others achieve more efficient resource use by doing things in new and novel ways.

Circular Bioeconomy Opportunities in Southern Arizona

- The wholesale trade, insurance, warehouse and storage, and scientific research and development service industries present areas where the Southern Arizona economy could expand to better serve existing bio- and circular- economy businesses. By shifting purchases from out-of-region suppliers to local Southern Arizona suppliers, a higher proportion of dollars would stay in the Southern Arizona economy.
- The case studies highlight the role of the University of Arizona in general and the Division of Agriculture, Life and Veterinary Sciences, and Cooperative Extension (ALVSCE) in particular as innovation catalysts for Southern Arizona. The two main hubs of the region’s circular bioeconomy are Tucson and Yuma. The university serves as a conduit for federal R&D funding and local expertise that joins and supports bio-economic activity across these hubs.
- A key theme amongst nearly all case studies is increasing efficiency and circularity in water use. These case studies illustrate Southern Arizona’s potential to be a testbed for 21st agricultural technologies for arid regions globally.
- Case studies demonstrate local expertise in controlled environment agricultural (CEA) systems. Such land- and water-saving systems may be transferable to a host of different urban contexts. Applications may even support future space exploration.
- Finally, the "Growing Our Own" (GOO) Initiative of Yuma County, Arizona and Imperial County, California illustrates how federal support along with the University of Arizona’s Land Grant University infrastructure (human capital, extension resources) can support STEM (Science, Technology, Engineering, and Math) workforce development in rural areas.

1. Introduction

Population growth, climate change, and urbanization all present significant challenges for our nation and the world alike. More than ever, societies face the realities of limited resources like water, food, energy, and environmental and human health degradation. To address these grand challenges, governments around the world are developing strategies for more efficient and more sustainable resource use.

One such strategy proposed in recent years is to foster and grow the ***bioeconomy***. Many view a well-developed bioeconomy as a critical component of the future economy and as a catalyst for addressing the world's greatest challenges, such as climate change, food security, energy independence, and environmental sustainability (Gallo, 2021). By embracing technological advancements (both within biological sciences as well as engineering, computing, and information sciences) and transitioning towards a more biology-based economy through the use of renewable biological materials (wood, manure, food waste, algae) for inputs and energy, the U.S. could achieve more sustainable development. Within the agricultural system, technological advancements could result in higher productivity and lower resource use. Additionally, a shift towards renewable biological materials could reduce the United States' use of petroleum-based fuels and products, thereby lowering its dependence on fossil fuels, a key driver of climate change (Gallo, 2021; Kardung et al., 2021; Daystar et al., 2018; Cho, 2017). Growth within the bioeconomy is a strategic target to, not only address environmental sustainability concerns, but also to be a source of new jobs and industries (Gallo, 2021). Economic development related to the bioeconomy could occur with job increases in rural and coastal areas where natural resources are concentrated, in industrial areas where transformed manufacturing processes could re-invigorate existing manufacturing industries, and in high-tech industries that develop and support innovative solutions and tools (Gallo, 2021; Hodgson et al., 2022).

Another strategy is to transition away from the current economic system that produces and consumes in a linear manner (harvesting raw inputs, transforming them into products, and then discarding them as waste) towards a circular system. A ***circular economy*** optimizes the use of energy, materials, and other resources and minimizes waste through reuse, sharing, repair, refurbishment, remanufacturing, and recycling (Loiseau et al., 2016; Venkatesh, 2021). In a circular economy, activities are shifted from a linear take-make-use-dispose paradigm to a closed-loop system (Loiseau et al., 2016; Venkatesh, 2021). The circular economy may then be described as "a system where value is retained throughout the lifecycle of materials; goods are designed for value retention, leakage is minimized through slowing, closing, or narrowing material and energy loops, and residues are seen as a resource input for further production" (Rogers et al., 2021). Transitioning to a circular economy is widely understood as congruent with a strong sustainability approach, focusing not only on improving resource efficiency, but also acknowledging and respecting our limited natural resources and engaging in economic activities that are disconnected from the use of finite resources (Tan and Lamers, 2021; Loiseau et al., 2016). Economic development focused on the circular economy could bolster new businesses and employment opportunities by expanding repair, reuse, and remanufacturing industries, creating jobs in high unemployment regions, and addressing knowledge and skill gaps of those unemployed with occupations in this sphere (Morgan and Mitchell, 2015; Llorente-Gonzalez and Vence, 2020).

At the intersection of these two emerging concepts is a third approach gaining national and international attention: the ***circular bioeconomy***. While there are various interpretations of what constitutes a circular bioeconomy and the relationship between the two concepts is complex, the synergies between advancing the bioeconomy and the circular economy are significant (Kardung et al., 2021; Tan and Lamers, 2021). One can characterize the circular bioeconomy as the minimization and utilization of waste, the use of resource-efficient value chains, the replacement of non-renewable resources with renewable resources, and the pursuit of cascading use (Carus and Dammer, 2018). More broadly, a circular bioeconomy is concerned with what resources are used (renewable biological resources) and how they are used (sustainably, with resource conservation as the primary motivation) (Venkatesh, 2021). Developing a circular bioeconomy is appealing based on the belief that a "transition to a restorative and regenerative circular bioeconomy will herald a renewal in competitiveness in the global economy, environmental sustainability, positive economic development and employment generation in the years to come" (Venkatesh, 2021).

While there is significant interest in growing these areas of the economy, monitoring progress requires establishing a baseline. Establishing a baseline for the bioeconomy and circular economy are challenging for several reasons. First, there are no standardized definitions for these two concepts. This presents a challenge because differing definitions result in inconsistencies in *what* is being measured. Various groups define the bioeconomy and circular economy differently depending on their affiliation and motivation. Definitions also vary geographically depending on the local biological resources (crops, forests, fish, etc.), the existing and emerging industries within the region, and the potential opportunities for co-location of biological resources and industries that can employ cascading use by utilizing waste streams. Second, by their very nature, the bioeconomy and circular economy are multi-disciplinary, inter-sectoral, and not easily characterized by existing industry classifications. This presents a challenge because federal statistics and other data related to the bio and circular economies are limited or unavailable at a fine enough distinction to capture components inside and outside of the proposed definitions. This is particularly the case for capturing economic activity related to new and emerging processes. For example, regular data series do not exist that separate plastics made from biobased materials or recycled materials from the larger plastics manufacturing sector. Nevertheless, to foster the bioeconomy, circular economy, and circular bioeconomy, it is important to first understand these concepts, establish a baseline through which to measure their role, and quantify their importance within the regional economy of interest.

This study defines the bioeconomy and circular economy within Southern Arizona (Cochise, Pima, Santa Cruz, and Yuma counties) and assesses the size, composition, and total contributions of each to the greater Southern Arizona economy. First, we develop conceptual and operational frameworks for identifying industries within the bioeconomy and the circular economy. We then use a variety of data sources to characterize the bioeconomy and circular economy landscape in Southern Arizona, presenting county-level and regional industry statistics for 2019. Following that, we present the results of the economic contribution analyses, which estimate the total contribution of bioeconomy and circular economy activities to the Southern Arizona regional economy, including multiplier effects. This includes jobs, income, value added, and sales supported directly by industries within the bioeconomy and circular economy as well as industries that are supported indirectly through multiplier effects.

Finally, presented as case studies, we identify and explore research, innovation, and commercialization efforts to grow the bioeconomy and circular bioeconomy in Southern Arizona.

2. Defining and Measuring the Bioeconomy and Circular Economy

Measuring, promoting, and monitoring the growth of the bioeconomy and circular economy require a consistent, standardized definition for both concepts. To date, a variety of terms are used, often interchangeably, to describe similar ideas. For example, the terms "bioeconomy" and "circular economy" are often used interchangeably with other related terms, including the "green economy," the "biobased economy" or the "circular bioeconomy."

Second, the bio and circular economies are, by their very nature, multi-disciplinary, inter-sectoral, and not easily characterized by existing economic sectors. The multi-disciplinary and inter-sectoral nature means that economic activities can span across many traditional economic sectors and there may not be data available at the level of detail needed to distinguish between biologically-based economic activity and non-biologically-based activity. The following section elucidates the conceptual and operational challenges of defining and measuring the bio and circular economies and defines them within the context of Southern Arizona.

2.1. Conceptual Definition

2.1.1. Bioeconomy

The first occurrence of the specific term "the bioeconomy" in print appeared in a publication of a commencement address at Vassar College in 1994, given by Dr. Bernadine Healy (1994), then director of the National Institutes of Health. Dr. Healy observed,

> "A revolution in the life sciences will also go way beyond medicine into agriculture, chemical production, environmental sciences, micro-electronics. Biotechnology will be creating jobs that we don't even have names for yet. And they will be high-paying, high-demand jobs—and intellectually satisfying ones. New industries will emerge that will be a growing source of national economic strength and world leadership. Some have gone so far as to suggest that the twenty-first century will be based on a bioeconomy."

The definition and conceptualization of the bioeconomy varies significantly across geographies as well as stakeholder groups, with some groups focusing on economic activity related to the ***production and use of biological resources*** while other groups focus more on economic activity associated with scientific breakthroughs and technological advancements enabled by ***research, innovation, and applications of biological and life sciences***. Furthermore, definitions can vary based on a region's natural resource base, its technological capacity, and its supporting infrastructure (Gallo, 2021).

The Appendix provides a timeline of U.S. policy initiatives and reports concerning the bioeconomy. Policy initiatives range from early programs to promote bio-energy crop production to the most recent Biden Administration Executive Order on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy.

Within European countries, the prevailing conceptual framework states that the bioeconomy "covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms, and derived biomass, including organic waste), their functions and principles. It includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries, and aquaculture); and all economic and industrial sectors that use biological resources or process them to produce food, feed, bio-based products, energy, and services" (European Commission (EU), 2018). Recent definitions have posited that the keyword characterizing the bioeconomy is "renewable," with a focus on the *types* of resources that are used, encompassing industries that are involved in the production and processing of *renewable* biological resources (Venkatesh, 2021). In effect, past economic contribution studies in the EU tend to have relatively broad definitions of the bioeconomy and include primary sectors (agriculture, forestry, and fisheries) as well as food, beverage, tobacco, and wood product manufacturing.

In contrast, the prevailing definition used in the United States, as described by the National Academies of Sciences, Engineering, and Medicine (NASEM), includes "economic activity that is driven by research and innovation in the life sciences and biotechnology, and that is enabled by technological advances in engineering and in computing and information sciences" (NASEM, 2020, p. 80). Advancements in the biological sciences have resulted in researchers being able to read an organism's genetic code, edit it with a high level of precision, or even create organisms with synthetic genomes (Gallo, 2021). This definition reflects a biotechnology-centric vision of the bioeconomy, where "activities in the bioeconomy center around generating scientific knowledge enabled by the purposeful manipulation of DNA, with production processes operating at the molecular level, the commercialization of such processes, and the development of new commercial products through biomanufacturing" (Gallo, 2021). While many of the scientific breakthroughs and innovations occur in specific sectors (such as in agricultural, biomedical, and bioindustrial sectors), the outcomes of a robust biotechnology-based bioeconomy include a solid applied research science base (often funded by the federal government and performed at universities or public research laboratories), significant data storage advancements, and data-intensive research processes that enable commercial innovations across a wide range of industries. A primary difference between U.S. and EU economic contribution studies, then, is that primary sectors (such as agriculture) are largely excluded from the U.S. bioeconomy definition, unless the crops produced are genetically modified (GM) or are grown specifically as biofuels for energy production (NASEM, 2020).

While these two conceptual frameworks for the bioeconomy have very different foci, some of their underlying concepts and objectives overlap. One of the most important public values associated with the bioeconomy is its potential to reduce the use of petroleum-based fuels and products, a key driver of climate change. Within both frameworks, there is an understanding that the bioeconomy will play a prominent role in reducing fossil fuel emissions by enabling a shift towards biological materials (wood, manure, food waste, algae) for inputs and energy. Doing so would rely on technologies such as genetically engineered microorganisms and/or technological advancements in chemical and industrial processes (Kardung et al., 2021; Daystar et al., 2018; Cho, 2017).

Another underlying concept common to both frameworks is sustainable production within agriculture and the broader food and fiber system. Sustainability achievements within the agricultural sector include smart (digital) farming techniques such as precision agriculture and application of biotechnology, bioengineering, and recombinant DNA technologies in developing herbicide-, insect-, and drought-resistant crops (Kardung et al., 2021). While both frameworks and related processes require technological advancements (either in computing and information sciences or biological sciences), under the U.S. more restrictive definition, economic activity associated with much conventional agriculture would not be included within the bioeconomy, but economic activity associated with the production of biofuel or genetically modified crops would.

Aside from these similarities, there are significant differences between the two bioeconomy definitions and conceptual frameworks. Whereas the broader EU definition wholly includes all primary sectors (agriculture, fisheries, and forestry), as well as sectors that manufacture and process biologically produced resources (Lier et al., 2018; Ronzon et al., 2017; Ronzon and M'Barek, 2018), the U.S. definition includes only select parts of primary sectors (genetically modified (GM) crops or crops produced for biofuels) and plant biomass processing using recombinant DNA technology to produce biobased chemicals and enzymes used in manufacturing products (Gallo, 2021; NASEM, 2020, p. 95). Other differences exist in the treatment of healthcare and medicine. The U.S. definition includes economic activity related to biopharmaceuticals, biologics (enzymes), and other pharmaceutical products, or health biosciences writ large, whereas the EU definition explicitly excludes them (Gallo, 2021; NASEM, 2020, p. 97). Also, many EU definitions exclude biotechnology R&D. Finally, the U.S. definition attempts to capture economic activity taking place within industries in the bioeconomy innovation ecosystem. This includes economic activity in bioeconomy research and development (R&D) by the government, universities, and private businesses, as well as economic activity in industries that support or enable advancement of biotechnology or life science research (Gallo, 2021; NASEM, 2020). For more discussion of international differences in bioeconomy definition and measurement, see Frisvold et al. (2021).

Further complicating application of a consistent conceptual framework is the fact that the term "bioeconomy" is often used interchangeably with other related terms, including the "green economy," the "biobased economy," the "circular economy," and the "circular bioeconomy." The "green economy" is generally considered to be an umbrella concept, encompassing both the bioeconomy and circular economy, with initiatives aimed at achieving environmental benefits (climate change mitigation, reducing biodiversity losses, etc.), economic benefits (economic growth, job creation, accelerated innovation, etc.), and social benefits (increased resilience, poverty reduction, etc.) (Loiseau et al., 2016).

Yet, some researchers have distinguished the bioeconomy from the circular economy according to the strength of its links to sustainability. Loiseau et al. (2016) argue that the bioeconomy, by itself, has a weak link to sustainability. A weak sustainability framework assumes that natural capital can be substituted by human capital (Loiseau et al., 2016). For example, using biotechnology as an approach to conserve resources assumes that society will always be able to meet increasing human need with limited natural resources through new technologies and innovation. This contrasts with the concept of strong sustainability, which assumes that natural capital and human and human-made capital are complementary, but not substitutes. Strong sustainability holds that there are critical thresholds of natural capital stocks and assumes that society must make structural changes to live "within its means" (Loiseau et al., 2016). A circular economy is an example of a strong sustainability approach.

2.1.2. Circular Economy

Like the bioeconomy, the "circular economy" does not have a single universal definition. In fact, Tan and Lamers (2021) found over 100 different definitions of the "circular economy," with the overall goals consistent across each definition but differences in how it is actually defined or measured. A "circular economy" can be defined as an economic system that aims to minimize waste and optimize the use of energy, materials, and other resources through reuse, sharing, repair, refurbishment, remanufacturing, and recycling, ultimately shifting activities from a linear take-make-use-dispose paradigm to a closed-loop system (Loiseau et al., 2016; Venkatesh, 2021). Other definitions couch the circular economy squarely within the 4R framework: reduce, reuse, repair, and recycle. A circular economy achieves efficiency by "slowing, narrowing, and closing material loops to reduce resource consumption and system waste via input reductions, sustainable design, improved practices, water reuse, and recycling" (Tan and

Lamers, 2021). Slowing extends the useful life of goods, narrowing uses fewer or different inputs to minimize the environmental footprint, and closing works to ensure that products are recycled or composted at end of life (Tan and Lamers, 2021).

According to the Ellen MacArthur foundation, the circular economy is based on three principles: (1) the elimination of waste and pollution, (2) keeping materials in use, either by repairing or reusing products or, when the product can no longer be used, by breaking the product into its component parts to recycle or reuse raw materials, and (3) shifting from extraction of natural resources to regeneration of natural resources by returning biological materials in natural systems. These three principles are underpinned by a transition away from the consumption of finite resources toward renewable energy and materials. An important component of this is preventing waste in the first place, the first priority in the waste management hierarchy (Figure 1). Advocates of the circular economy argue that by shifting our mindset, the generation waste should be considered a design flaw. In other words, advocates of the circular economy argue that every effort should be pursued to prevent waste, starting first by designing products for maintainability, reparability, recyclability, and recoverability.

FIGURE 1. WASTE MANAGEMENT HIERARCHY

Source: Axil Integrated Services Limited, 2018

Many researchers consider the bioeconomy, circular economy, and sustainability to be three different concepts with overlapping 'trends' or objectives (De Oliveira et al., 2018; Venkatesh, 2021). While there tends to be agreement on the goals of the concepts, there are disagreements on how each of these topics are defined and measured, making them "essentially contested concepts" as coined by Gallie in 1956 (Tan and Lamers, 2021; Gallie, 1956).

One can describe the relationship between the bioeconomy and circular economy as: (1) separate but reinforcing, (2) completely integrated, (3) partially antagonistic, (4) with the bioeconomy as a precondition to the circular economy, or (5) with the circular economy serving as a tool to move from a fossil fuels-based economy to a bioeconomy (Tan and Lamers, 2021; Leipold and Petit-Boix, 2018). Nevertheless, efforts exist to promote greater integration of each concept by focusing on the intersection of these two themes.

2.1.3. Circular Bioeconomy

A “circular bioeconomy” is commonly defined as the “intersection of the bioeconomy and circular economy” (Carus and Dammer, 2018). It is an economy in which “side streams from renewable bioresources are looped back into the technosphere – open or closed recycling or conversion from matter to energy” (Venkatesh, 2021). Generally, a circular bioeconomy is characterized by minimization and utilization of waste, resource-efficient value chains, replacing non-renewable resources with renewable resources, and cascading use. In its most common application, primarily within the EU, strategies aim to maximize biobased resources and minimize waste by using biobased wastes (such as agricultural and forestry residues) as inputs to other production, either biobased products or bioenergy. More recent definitions have embraced the role that technological advancements have in shifting away from the traditional “linear” economic model. The Schmidt Futures Foundation’s Task Force on Synthetic Biology and the Bioeconomy has defined the circular bioeconomy as “an economy that forgoes the traditional linear economic model of ’take-make-consume-throw away‘ for one that uses the power of biotechnology, design for bioproduction, and machine learning/artificial intelligence to create an economic system in which waste products serve as inputs to create highly valued products and materials, that are used as long as possible, and reused without drawing down limited resources or generating wastes that are disposed into the atmosphere, landfills, or rivers, lakes, and oceans” (Hodson, et al., 2022, p. 2).

There are components within the bioeconomy that are not necessarily part of the circular economy and vice versa. For example, while many industries within the bioeconomy may be oriented towards resource conservation (such as precision agriculture, gene editing, and soil, plant, and animal sensors), they do not adhere to the circular ‘reuse, repair, and recycling’ approach. Meanwhile, some industries within the bioeconomy do not meet the circular economy definition (Carus and Dammer, 2018). An example of this is the use of biomass for bioenergy production. Once biomass is used for energy production, it is lost for cascading use. The circular economy includes both renewable and non-renewable resources, with much of the economic activity occurring outside of the biological sphere. For example, many circular economy activities strive to minimize e-waste, which involves maintenance and repair of electronic products and reuse to reduce electronic waste, one of the fastest growing waste streams globally (Svensson et al., 2018; Rogers et al., 2021).

Currently, there are numerous impediments to repair in the electronic space including legal barriers such as intellectual property right infringements, design barriers where products have been designed for obsolescence, or access and cost of repair as opposed to purchasing new products (Svensson et al., 2018). Recently, some state legislatures have been introducing Right-to-repair acts designed to combat planned obsolescence or to allow for repairs by third parties rather than the original equipment manufacturers (OEMs) (Svensson et al., 2018). On July 9, 2021, President Biden signed an Executive Order on Promoting Competition in the American Economy (White House, 2021). Among other initiatives, the Order encourages the Chair of the Federal Trade Commission (FTC) to, “exercise the FTC’s statutory rulemaking authority, as appropriate and consistent with applicable law, in areas such as … unfair anticompetitive restrictions on third-party repair or self-repair of items, such as the restrictions imposed by powerful manufacturers that prevent farmers from repairing their own equipment.” In January 2023, the American Farm Bureau Federation and John Deere signed a Memorandum of Understanding that would give farmers more latitude in repairing their equipment (Harrington, 2023).

2.2. Operational Definition

In addition to a lack of consistent conceptual definitions for the bioeconomy and circular economy, there is also a lack of available data to quantify the economic contribution of the bioeconomy, the circular economy, and its component parts. Their multi-disciplinary and inter-sectoral nature means that economic activities can span across many traditional industries, and often not in their entirety.

The most common way to measure the economic contribution of an industry involves use of economic data available by industry NAICS code (North American Industry Classification System). The NAICS is the official system used by the federal government to classify establishments by the types of activities they are engaged in. Establishments are grouped by production processes and are categorized hierarchically such that industries are divided into 2-digit to 6-digit NAICS codes, with each digit providing increasingly more detailed classifications. For example, NAICS 11 is the economic sector that includes all agricultural activities (crop and livestock production) as well as forestry, fishing, and hunting activities. A 6-digit NAICS provides a more detailed description of economic activities, such as the crop that is being grown. For example, NAICS 111335 is comprised of establishments primarily growing tree nuts.

2.2.1. Biobased Industries vs. Biobased Activities

NAICS codes often do not use a granular enough level of detail to distinguish between economic activities pertaining to the bioeconomy from that which is not. So, while a common approach to measuring the contribution of the bioeconomy is to assign industries as wholly included or wholly excluded from the bioeconomy based on their NAICS code, a key issue is that many industries may engage in both biobased and non-biobased activities, with data unavailable to split these activities out (NASEM, 2020). For example, within the plastics manufacturing industry (which, as a whole, would be excluded from the bioeconomy), a portion of economic activity involves production of bioplastics, which would be included in the bioeconomy. Data availability to tease out "biobased" activities, however, is extremely limited. Thus, to measure those activities, a common approach is to develop estimates using primary data collection such as establishment-level surveys (NASEM, 2020).

Notably, data availability is one of the major benefits of using a broad definition of the bioeconomy. Including primary sectors (agriculture, forestry, and fisheries) and food and feed processing industries in their entirety allows for use of readily available federal statistics. A drawback of this approach, however, is that it does not capture innovations occurring in these spaces. In fact, many of these mature industries have experienced decreasing wages and income over time, which is not representative of the innovation ecosystem that has developed through applications of biological research and/or biotechnology (NASEM, 2020).

2.2.2. Circular Industries vs. Circular Activities

The circular economy concept suffers from similar issues. Circular activities and practices can take place across many industries. NAICS codes can be used to identify ***industries*** that are primarily engaged in reuse, repair, and recycling and that derive their sales from those products and services, but to our knowledge, no regularly-collected data exist that describe the extent to which circular activities and practices exist ***within existing industries***. For example, businesses have programs to recycle paper, plastic, aluminum, or printer cartridges. Data on spending, labor time, etc. devoted to such ***activities*** are not readily available. Data are available, however, for ***establishments*** in recycling industries. In fact, for statistical purposes, businesses are categorized by their economic activity which generates the most sales. If they are generating and selling byproducts or waste as inputs to the production processes of other businesses, that is unlikely to be captured in federal statistics. Similarly, if they are using byproducts or wastes of other industries as inputs to production, that circular linkage is not captured in standard economic statistics.

While capturing circular activities within industries is not possible due to data limitations, one can measure economic activity taking place in businesses that operate in existing repair, reuse, and recycling industries. These circular industries can act as useful proxies and serve as a baseline for the current scale of the circular economy in Southern Arizona.

2.3. Southern Arizona's Bioeconomy and Circular Economy

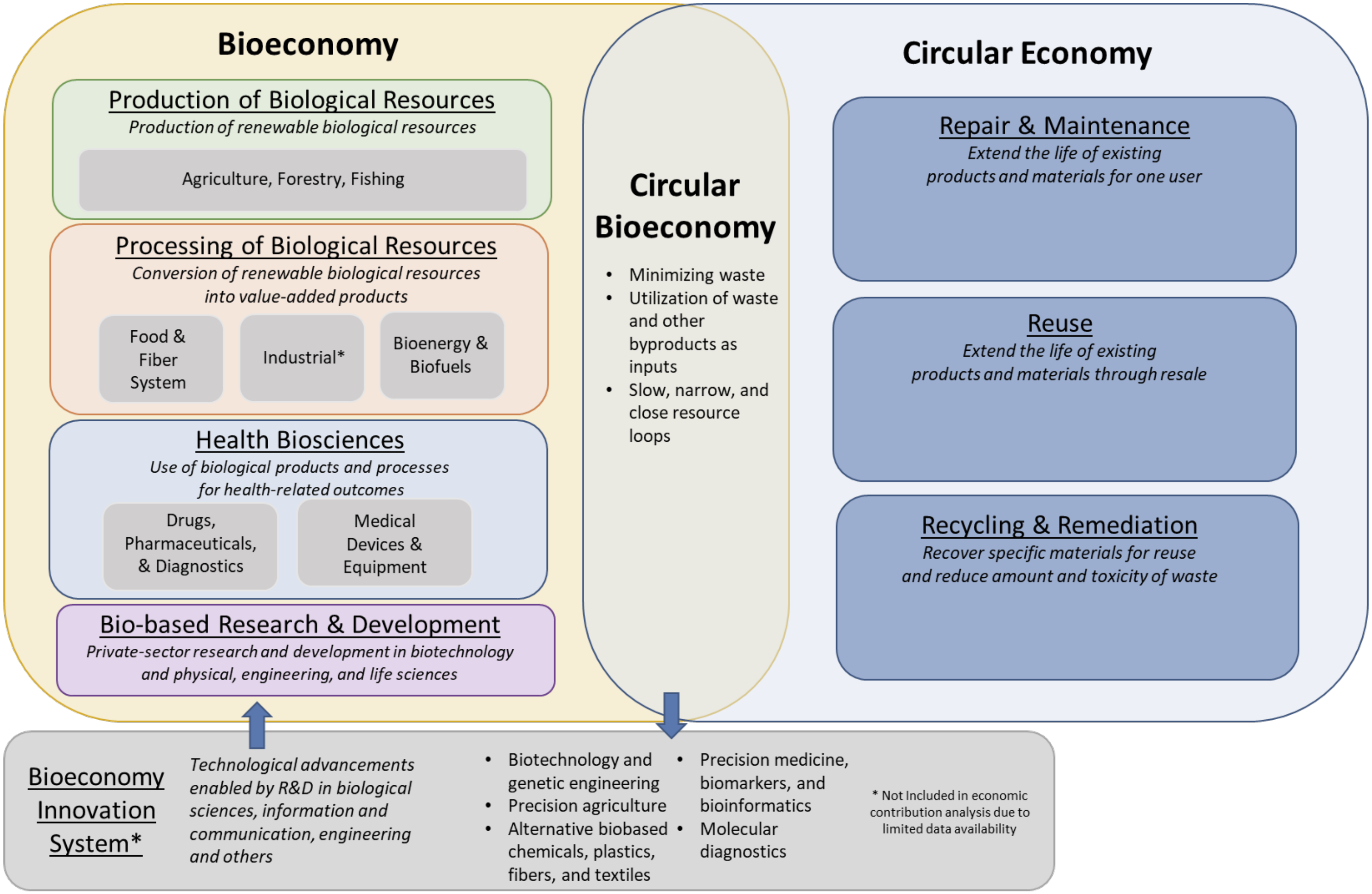
This study develops a conceptual and operational framework for bioeconomy and circular economy in Southern Arizona. A regional approach to conceptualize and measure this activity is helpful for several reasons. First and foremost, given that access to renewable biological resources (crops, forests, fish, etc.) will primarily involve rural communities, many aspects of the bioeconomy will occur at the local and regional scale, coupling the industries and specializations of both urban and rural areas. Efforts to further develop the bioeconomy should be targeted based on the region's attributes, strengths, and opportunities and economic development initiatives are likely to be most effective when considering potential economic clusters based on existing and emerging regional industries (Gallo, 2021; Kardung et al., 2021). Second, promotion of circularity – particularly within the bioeconomy – is enhanced by the co-location of biological resources and industries that can employ cascading use by, for example, utilizing waste streams (Carus and Dammer, 2018; Hodgson et al. 2022).

2.3.1. Conceptual Framework

Figure 2 presents the conceptual framework for the Southern Arizona bioeconomy and circular economy. For purposes of this study, a relatively broad definition of the bioeconomy is adopted, blending the EU and U.S. definitions and conceptual frameworks. The Southern Arizona ***bioeconomy*** landscape is divided into four components: (1) Production of Biological Resources (plants, animals, micro-organisms), (2) Processing of Biological Resources, (3) Health Biosciences, and (4) Bio-based Private Sector Research and Development.

Although a relatively broad definition for the "bioeconomy" is adopted for this study, it is not comparable with previous studies of the "Bioscience Industry" in Arizona (Battelle, 2006; Battelle, 2014). One of the primary differences in the definition is the treatment of health-related biosciences. Previous studies focus more on the role of healthcare and its related industries, and include all economic activity taking place in hospitals, research, testing, medical labs, and more recently, economic activity in industries that distribute biomedical equipment and supplies and medication. Another difference is that previous studies do not include economic activity related to the production of plants and animals on Arizona's farms and ranches nor do they include any type of processing.

FIGURE 2. RELATIONSHIP BETWEEN THE BIOECONOMY AND CIRCULAR ECONOMY



Adapted from Carus and Dammer, 2018; Kardung et al., 2021

Industries that ***use or produce renewable biological resources*** include agriculture, forestry, and fishing and are an essential component of the bioeconomy. Our definition of biological or biomass production and processing is not confined to bio-based energy production. Rather it includes all renewable biological resources (agriculture, forestry, and fisheries). Industries that ***process or convert these renewable biological resources into value added products*** are also part of the bioeconomy and occur within the food and fiber system, within industrial or chemical industries, or within the renewable energy industry through the use of bioenergy and biofuels. A third set of industries ***use biological products and processes for health-related outcomes***, including industries involved in developing medicines, pharmaceutical products, diagnostics, and medical devices and equipment. Finally, there are private industries that ***support and enhance the advancement of the bioeconomy through research and technological advances in biological sciences, engineering, and computing and information sciences*** (NASEM, 2020).

The ***circular economy***, on the other hand, focuses on minimizing waste and optimizing resources use through reuse, sharing, repairing, refurbishing, remanufacturing, and recycling (Figure 2). The circular economy includes industries that ***extend the life of existing products or materials for their original user, a subsequent user, or that recover specific materials for a new product***. Specifically, the circular economy includes industries involved in: (1) Repair and Maintenance, (2) Reuse and Resale, and (3) Recycling and Remediation.

This study examines the economic contribution at the union of the circular economy and the bioeconomy. In other words, the study wholly includes economic activity within bioeconomy industries as well as economic activity within circular industries. This is synonymous with the conceptual definition of the "Green Economy" developed by Kardung et al. (2021). In contrast, Section 6 provides some examples of activities that occur at the intersection of the bioeconomy and circular economy as well as research and innovative efforts within the bioeconomy innovation ecosystem.

2.3.2. Operational Framework

In order to operationalize this framework, we categorize industries by NAICS codes. Table 1 presents a full list of industries within the Southern Arizona ***bioeconomy*** and their corresponding NAICS codes and IMPLAN sectors, aggregated to four overarching categories: (1) Production of Biological Resources (plants, animals, micro-organisms), (2) Processing of Biological Resources, (3) Health Biosciences, and (4) Bio-based Private Sector Research and Development. Similarly, Table 2 presents the full list of industries within the Southern Arizona ***circular economy***, aggregated to three main categories (Repair & Maintenance, Reuse & Resale, and Recycling & Remediation) and their corresponding NAICS codes and IMPLAN sectors. Given data limitations, the contributions of the bioeconomy and the circular economy to Southern Arizona are estimated separately.

TABLE 1. SOUTHERN ARIZONA BIOECONOMY INDUSTRIES WITH CORRESPONDING NAICS AND SECTOR CODES

IMPLAN Sectors	NAICS Code	NAICS Code Description
Production of Biological Resources		
1-10	111	Crop production
11-14	112	Animal Production and Aquaculture
15-16	113	Forestry and Logging
17-18	114	Fishing, Hunting, and Trapping
19	115	Support Activities for Agriculture & Forestry
Processing of Biological Resources		
Food and Fiber System		
63-103	311	Food Manufacturing
104-109	312	Beverage and Tobacco Product Manufacturing
110-116	313	Textile Mills
129	3161	Leather and Hide Tanning and Finishing
Bioenergy		
45	221117	Biomass Electric Power Generation
163	325193	Ethyl Alcohol (Ethanol) Manufacturing
Industrial		
163	325194, 325199	Other Basic Organic Chemical Manufacturing
167-170*	3253	Pesticide, Fertilizer, and Other Ag Chemical Manufacturing
Health Biosciences		
171-174	3254	Pharmaceutical and Medicine Manufacturing
311	334510	Electromedical and Electrotherapeutic Apparatus Manufacturing
317	334516	Analytical Laboratory Instrument Manufacturing
318	334517	Irradiation Apparatus Manufacturing
376	339112	Surgical and Medical Instrument Manufacturing
Bio-based Private Sector Research and Development		
464*	541714	Research and Development in Biotechnology (except Nanobiotechnology)
464*	541715*	Research and Development in the Physical, Engineering, and Life Sciences (except Nanotechnology and Biotechnology)

* indicates industries with only a portion of economic activity within the bioeconomy

TABLE 2. SOUTHERN ARIZONA CIRCULAR ECONOMY INDUSTRIES WITH CORRESPONDING NAICS AND SECTOR CODES

IMPLAN Sectors	NAICS Code	NAICS Code Description
Repair and Maintenance		
512	8111*	Automotive Repair and Maintenance
514	8112	Electronic and Precision Equipment Repair and Maintenance
515	8113	Commercial and Industrial Machinery Repair and Maintenance
516	8114	Personal and Household Goods Repair and Maintenance
Reuse and Resale		
392*	423140	Motor Vehicle Parts (Used) Merchant Wholesalers
402*	441120	Used Car Dealers
412*	453310	Used Merchandise Stores
417*	484210	Used Household and Office Goods Moving
Recycling and Remediation		
479*	562910	Remediation Services
479*	562920	Materials Recovery Facilities
396*	423930	Recyclable Material Merchant Wholesalers

* indicates industries with only a portion of economic activity within the circular economy

2.4. Innovation Ecosystem Supporting Bioeconomy and Circular Bioeconomy

Supporting the bioeconomy, circular economy, and the circular bioeconomy is the ***innovation ecosystem***, which reflects ***technological advancements enabled by research and development (R&D) in biological sciences, information and communication, engineering, and others***. Jackson (2011) has highlighted similarities between biological ecosystems and innovation ecosystems. Biological ecosystems are characterized by energy relationships between living things (including humans) and their habitats, with a goal of sustaining system functions. Innovation ecosystems are characterized by economic relationships between agents and entities, with a goal of sustaining technology development an innovation processes. The agents and entities in an innovation ecosystem include "universities, … venture capitalists (VC), industry-university research institutes, federal or industrial supported Centers of Excellence, and state and/or local economic development and business assistance organizations, funding agencies, policy makers, etc. (Jackson, 2011)." Entities in an ecosystem are proximately located and linked strategically to focus on developing specific technologies.

Reichert (2019) led an EU study considering the "central role" of universities in the innovation ecosystem "orchestrating multi-actor innovation networks." The study focused on linkages between European universities, regional partners, and international networks. As the circular economy moves away from a linear use system, Reichert (2019) movers from a conception of "innovation as a linear process that leads from basic via applied research to commercialization along a continuous line" instead to a 'a reiterative process" where basic and applied research and commercial prototype development mutually enhance each other, creating productive feedbacks.

R&D at universities or public research laboratories has historically played a significant role in advancing the bioeconomy. Much of the basic and applied research leading to enabling, foundational science is the result of federal funding and academic research (Hodgson et al., 2022). In the U.S., recent legislation has acknowledged the role of land-grant universities in supporting and growing regional bioeconomies (Gallo, 2021).

While some advancements follow the "educational-industrial complex" model (the linear process), whereby governments fund basic research and the private sector manages their application and commercialization, public institutions do play a role in supporting advancement and commercialization of bioeconomy-related innovations by convening groups and providing physical spaces and infrastructure, such as pilot facilities (Zilberman, 2018; Gallo, 2021). These facilities offer low-risk opportunities for translational research and scaling up commercialization efforts. This also applies to the digital space where improved management and access to biological data could lead to important scientific discoveries and innovations. In these cases, public institutions are addressing technological challenges and serving as a conduit for commercialization.

While private sector economic activity related to R&D within the bio- and circular economy is captured in the conceptual framework above, summarizing economic activity associated with public R&D in the bioeconomy and circular bioeconomy is incredibly challenging. This is, in part, due to the fact that research funding in these areas is often categorized by high-level disciplines, such as "life sciences" (NASEM, 2020) as well as their status as intangible assets. Intangible assets include non-physical assets derived as a result of investment in innovation activities. Intangible investments include spending on knowledge creation or improved product or processes that are expected to yield a future return. Examples include R&D, software, databases, new product development, employee training; and business process improvements, among others. Examples of intangible assets are patents, licenses, copyrights, trademarks, industry-specific human capital, and operating models, processes, and systems (see Box).

The value of intangible assets in the bioeconomy cannot be measured as other aspects of the bioeconomy by relying on data from systems of national or regional economic accounts. The NASEM report's Chapter 3 outlined methods and presented results for measuring bioeconomy intangible assets using growth accounting and permanent inventory methods, on a somewhat experimental and preliminary basis. To our knowledge, this is the only attempt to include intangible assets in measurements of a bioeconomy. Because of limited data availability, this component is beyond the scope of this study is not included in the economic contribution analysis. While such activity is difficult to quantify, we follow approaches used in previous studies (Reichert, 2019; Hodgson et al., 2022) and consider the innovation ecosystem for the Southern Arizona bioeconomy through a series of case studies (see Section 6).

Public institutions also provide critical education and training for the future bioeconomy workforce. There is broad consensus that a skilled workforce is essential to advancing the bioeconomy (Gallo, 2021). Education and curricula related to Science, Technology, Engineering, and Math (STEM) fields are seen as important drivers of workforce development in this area. To date, much of these efforts have centered around biotechnology, with little emphasis on bioprocessing (NASEM, 2020).

In agricultural settings the innovation ecosystem includes modern biotechnologies such as genetically modified organisms (GMOs) and CRISPR (gene editing), which have shown to increase the speed and precision of plant breeding, resulting in increased yields, lower costs, and a reduction in the land and environmental footprint of agriculture (Zilberman et al., 2018). It also includes technological advances in computing and information sciences such as precision agriculture, which uses high-tech sensors and/or satellite- or unmanned aerial vehicle (UAV) technology (Combs et al., 2022) to monitor, assess, and determine optimal fertilizer, water (Elshikha et al., 2022), or pesticide application (Friedl, 2018). Innovation also occurs within food and fiber manufacturing and industrial processes, reflecting companies and industries that have shifted from producing petroleum-derived products (chemicals, plastics, textiles, etc.) to biobased products, utilizing agricultural and forestry feedstocks as inputs. An example is bioplastics, which are manufactured from "renewable biomass, such as vegetable oil, cornstarch, pea starch, and microbiota" (Daystar, et al., 2020). Finally, breakthroughs in biomedical and health biosciences are driving advances in the pharmaceutical, medical device, and healthcare industries (NASEM, 2020). Within the circular economy, there is great potential for R&D and innovation in waste utilization. Successes in this area could enable municipal solid waste streams to be recovered and recycled rather than disposed of. Research is needed to develop and improve the technologies and infrastructure necessary to manage circularity in municipal waste streams (U.S. Department of Energy, 2020). Nonetheless, there is strong potential to use municipal solid waste as feedstock for biofuels and bioproducts production (U.S. Department of Energy, 2020).

BOX 1: INTANGIBLE ASSETS

Intangible assets, broadly defined, are non-physical assets that are derived as a result of investment in innovation activities. In other words, spending on knowledge creation or improved product or processes that are expected to yield a return in future periods. This includes spending on research and development (R&D); software, database, and new product development; employee training; and business process improvements, among others. Examples of intangible assets are patents, licenses, copyrights, trademarks, industry-specific human capital, and operating models, processes, and systems.

Within the bioeconomy, many intangible assets are held or promoted within the public sector. This is particularly the case for information intangible assets or data. The public sector has played a large role in the collection, curation, and distribution of data for public and private use, some of which have spurred commercial application and economic development in the private sector. One example of this is the National Center for Biotechnology Information (NCBI), a division of the National Library of Medicine (NLM) at the National Institutes of Health (NIH). The NCBI is involved in "creating automated systems for storing and analyzing knowledge about molecular biology, biochemistry, and genetics; facilitating the use of such databases and software by the research and medical community; coordinating efforts to gather biotechnology information both nationally and internationally; and performing research into advanced methods of computer-based information processing for analyzing the structure and function of biologically important molecules" (NCBI, 2022). The NCBI has a Pathogen Detection project in collaboration with the Centers for Disease Control (CDC), Food and Drug Administration (FDA), and U.S. Department of Agriculture's Food Safety and Inspection Services (USDA FSIS) to sequence bacterial pathogens, identify potential outbreaks, and facilitate investigations and responses to outbreaks (NCBI Resource Coordinators, 2016). An example connected to *the University of Arizona is CyVerse, an NSF-funded project dedicated to providing solutions for data management, storage, analysis, and visualization, among other services. The solutions provided by CyVerse are oriented towards addressing the needs of scientists in life sciences and bioinformatics. Today, CyVerse has over a hundred thousand researchers using the platform across 160 countries and has been cited in over 1,500 peer reviewed publications.*

The public sector also plays a critical role in developing human capital assets or a skilled bioeconomy workforce. Innovations within the bioeconomy have arisen as a result of the convergence of disciplines such as life sciences, engineering, and computer sciences (Gallo, 2022). As such, the education and training for future bioeconomy workforce should also be multi-disciplinary in nature.

3. Data and Methods

This study uses a variety of data sources to estimate the size, composition, and total economic contribution of the bioeconomy and circular economy in Southern Arizona. The contributions of the bioeconomy and the circular economy to the broader Southern Arizona economy are estimated separately. We examine establishment, employment, and wage data from the Bureau of Labor Statistics' (BLS) Quarterly Census of Employment and Wages (QCEW), agricultural data from the U.S. Department of Agriculture's (USDA) 2017 Census of Agriculture, county-level economic data from the U.S. Department of Commerce's Bureau of Economic Analysis (BEA), as well as regional economic data from the proprietary input-output software program, IMPLAN.

3.1. Economic Contribution Analysis

The regional economic contributions of the bioeconomy and circular economy are estimated through an economic contribution analysis. An economic contribution analysis presents a snapshot of economic activity supported or attributed to the existence of an industry or cluster of industries at a given point in time and within a specific geographic area. The study area for this analysis is Southern Arizona, including Cochise, Pima, Santa Cruz, and Yuma counties. The year of analysis is 2019. We use 2019 as a base-year because it is the last full year prior to the COVID-19 pandemic when many economic relationships were affected and are not necessarily representative of "business as usual."

The activities of individual industries or clusters of industries contribute to a regional economy through what are known as *economic multiplier effects*. Economic activity that takes place within the industry being studied are called *direct effects*, economic activity that takes places in industries that provide inputs to the industry are called *indirect effects*, and economic activity that take places in industries that provide household goods and services to people employed by the industry are called *induced effects*. Indirect and induced multiplier effects are limited by leakage, however. Leakage occurs when inputs and other household goods and services are purchased from outside of the study area.

In the context of this study, direct effects capture the jobs, incomes, value added, and sales that occur directly within industries identified as part of the bioeconomy and circular economy. Indirect effects, then, capture economic activity that is generated through business-to-business transactions, or when bio- and circular economy businesses purchase inputs from other Southern Arizona businesses. Due to the broad definition of the bioeconomy, the range of inputs varies from agriculture-specific inputs such as land, water, and farm machinery and equipment to specialized equipment for biological resource processing and health-related bioscience manufacturing and research. Inputs to circular economy businesses include commercial and industrial machinery, warehouse and storage services, and general businesses services such as accounting, legal, and business support services. Induced effects capture economic activity when employees working within the bio- and circular economies spend their earnings on household goods and services, such as rent or mortgage, groceries, childcare, medical care, or simply going out to eat or to the movies. These are household-to-business transactions that support jobs, incomes, value added, and sales in consumer-driven industries.

3.2. Caveats and Considerations

This study uses NAICS codes to identify which industries are included within the bioeconomy and circular economy and which are not. As mentioned previously, many NAICS codes are not granular enough to distinguish between economic activity pertaining to the bioeconomy and circular economy from that which is not. Therefore, there may be many industries in Southern Arizona that are engaged in both biobased activities and/or circular activities that are not captured in this study. This is particularly the case for circular activities.

While this study accounts for industries explicitly involved in the "repair, reuse, and recycling business", it does not account for any circularity that may be occurring within an individual business, within an industry, or even a cluster of industries. This is due to a lack of available data. Data do exist by NAICS codes, grouping industries by the types or products and services they sell, but little to no information is available about the sources of inputs, the value of sales of byproducts which do not constitute a business's primary source of revenue, or the transfer of wastes or byproducts to other businesses without a monetary transaction.

Finally, due to data limitations, we do not develop estimates for the "circular bioeconomy." However, Section 6 of this report highlights activities within the circular bioeconomy in Southern Arizona through the use of case studies.

3.3. Case Studies

While the public, private, academic, and research sectors tend to operate independently from the confines and theoretical definitions of circular bioeconomy, we present in Section 6 a series of case studies that illustrate how this circularity and bioeconomy are partially or wholly implemented in Southern Arizona. This case study approach has been applied by the Schmidt Futures Foundation to assess the U.S. bioeconomy (Hodgson, et al., 2022) and by Reichert (2019) to examine the role of EU universities in innovation ecosystems.

In August 2022, a call for case studies was announced in the Cooperative Extension Tuesday Extension Notes. The call requested short, illustrative case studies of public and private R&D, programs, and education efforts tied to the bioeconomy, circular economy, or circular bioeconomy ongoing in Southern Arizona. The purpose of these case studies is to provide real-life examples of research and innovative efforts to grow the circular bioeconomy.

A key challenge to the region is climate change (Seager et al., 2007) and the question about dwindling water resources (Lahmers et al., 2018, Scott and Pasqualetti, 2010). Limited water is critical to the state and continues to jeopardize its urban centers, industries, and especially the agricultural sector. The state is now engaged in a long-term plan to reduce, reuse, and sustain its water resources. For example, new crops that maintain economic profits while reducing dependence on the Colorado river and underground water led to the revival of Guayule, a natural rubber producing shrub crop that was explored during the US Emergency Rubber Project (ERP) during World War II (Foster and Coffelt, 2005) as an emergency replacement of Southeast Asia natural rubber. Guayule is again being explored as a water saving crop with great potential for profitable natural rubber production and an array of byproducts that support bioeconomy that can afford local farmers an option to survive this water crisis. Bridgestone Americas Inc. (tire company) and the University of Arizona, and other regional institutions, funded by a USDA-NIFA grant, led a ten-year effort to develop a Guayule crop production industry focused on water saving and research for optimizing biomass production. While the effort crosses to the Pinal and Maricopa counties, Bridgestone efforts are mostly in Pima County and is heavily supported by the Department of Energy and USDA (Bridgestone, 2022). In Section 6 we present a case study on how Guayule is becoming a significant circular bioeconomic activity in the region, where the private sector, research institutions, and federal agencies are promoting this crop as an alternative to the more water consuming crops.

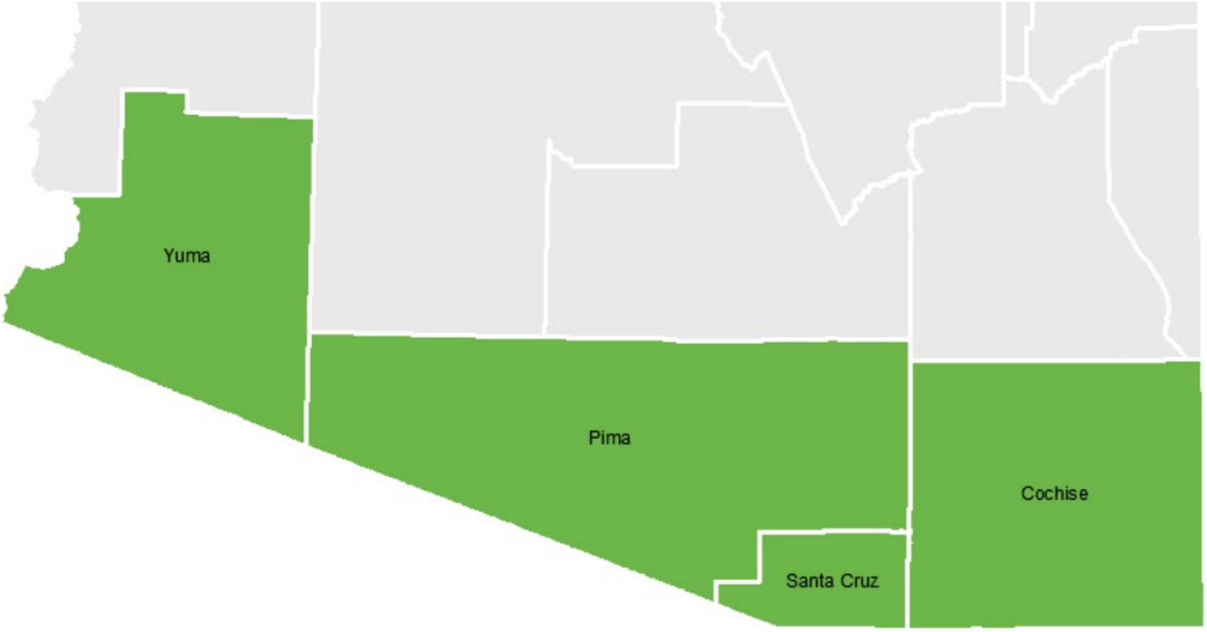
4. Southern Arizona's Bioeconomy and Circular Economy Landscape

The following section explores the bioeconomy and circular economy landscapes in Southern Arizona, presenting industry statistics for 2019, key trends, and regional statistics. Given the importance of co-location of renewable biological resources and capacity in existing industries that may utilize waste streams to promoting circularity within the bioeconomy, we also present key statistics at the county-level (where available). To begin, the following section provides an overview of the study region, presenting a brief regional profile and identifying top industries within each of the four Southern Arizona counties. We then present statistics related to each component of the bioeconomy and circular economy.

4.1. Regional Overview

The study region for this analysis is Southern Arizona, which for purposes of this analysis includes the four southernmost counties in the state: Yuma, Pima, Santa Cruz, and Cochise counties (Figure 3). All four of these counties have Mexico on their borders. Southern Arizona is home to the Tucson metropolitan area, as well as the communities of Yuma, Nogales, Rio Rico, Sierra Vista, Douglas, Bisbee, Benson, and Wilcox.

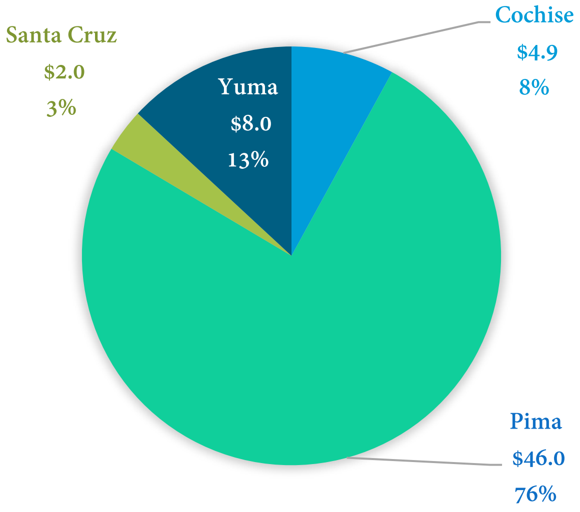
FIGURE 3. SOUTHERN ARIZONA COUNTIES



Top industries in Pima County include higher education, healthcare, and aerospace and defense (Duval et al., 2021). The county's largest metro area, Tucson, is home to the state's land grant university, University of Arizona. Santa Cruz County, south of Pima County, is the state's smallest county by land area. It is home to the city of Nogales which is known for its large fresh produce industry cluster, including transportation and wholesale industries related to the importation, storage, and transport of fresh produce from Mexico. Other significant industries in the county include government services, and agricultural industries, particularly ranching and a growing grape-growing and wine industry (Duval et al., 2021). Yuma County, the fifth most populous county in Arizona, is located in the southwest corner of the state, bordered to the west by California and the Colorado River. Characterized by its warm temperatures, arable land, and high priority water rights to Colorado River water, agriculture plays a significant role in the county economy. Eight (8) of the top 10 most concentrated private industries in the county are agricultural industries (Duval et al., 2021). Other top industries in the county include tourism, related to 'snow-bird' visitation, and government services, as the county is home to two military bases (Duval et al., 2021). Finally, Cochise County is in the southeastern corner of the state on the border with New Mexico to the east. Top industries in Cochise County include agriculture with a rapidly growing tree nut and winery industry, tourism, and government services, anchored by the Fort Huachuca Army base (Duval et al., 2021).

The combined population of the four counties was 1.4 million as of 2019, of which the Tucson metro area accounted for 73% (U.S. Census Bureau, 2020). The Tucson metro area lies within Pima County, the second most populous county in Arizona. In 2019, the Southern Arizona Gross Regional Product (GRP), analogous to national Gross Domestic Product (GDP), totaled $60.9 billion. Similar to population, Pima County accounts for roughly three-quarters of regional GDP (76%), with a county GDP of $46 billion (Figure 4).

FIGURE 4. GDP (BILLIONS) IN SOUTHERN ARIZONA BY COUNTY, 2019



Source: Bureau of Economic Analysis (BEA), 2019.

Total regional employment in 2019 was approximately 693,000 jobs in all four counties, combined (Table 3). Similar to GDP, Pima County accounts for about three-quarters of total regional employment with more than 530,000 jobs. Across all four counties, jobs within government and government enterprises, health care and social assistance, and retail trade account for the highest proportion of jobs. Employment in industries related to the fresh produce industry (wholesale trade and transportation and warehousing) account for a sizable share of total county employment in Santa Cruz County and employment related to farming and forestry, fishing, and agricultural support services (primarily due to employment associated with farm labor contracting) is a sizable share of total county employment in Yuma County (Table 3). At this high-level aggregation of industries (2-digit NAICS codes), identification of sectors within the bio- and circular economies is not possible.

While raw employment data from federal statistics are useful for understanding which industries support the most jobs within a county, a common way to assess the economic specialization in a county is to conduct an economic base analysis. Using an analytical tool called location quotients (LQs), an economic base analysis determines the relative concentration of an industry within a local economy by analyzing the industry's share of local employment relative to the national average (Siegel, et al., 1995).

Table 3. Employment In Southern Arizona by County and High-Level Industry, 2019

High-Level Industry	Cochise	% of Total Jobs	Pima	% of Total Jobs	Santa Cruz	% of Total Jobs	Yuma	% of Total Jobs
Farm employment	1,381	2.7%	1,145	0.2%	481	2.3%	3,822	4.2%
Forestry, fishing, agricultural support services, & related activities	465	0.9%	421	0.1%	(D)	(D)	8,935	9.9%
Mining, quarrying, and oil and gas extraction	205	0.4%	3,417	0.6%	(D)	(D)	84	0.1%
Utilities	316	0.6%	2,184	0.4%	56	0.3%	185	0.2%
Construction	2,687	5.2%	26,560	5.0%	735	3.6%	4,399	4.9%
Manufacturing	851	1.6%	30,036	5.7%	617	3.0%	2,894	3.2%
Wholesale trade	575	1.1%	8,759	1.7%	2,249	10.9%	1,673	1.9%
Retail trade	5,659	11.0%	50,708	9.6%	2,404	11.7%	9,570	10.6%
Transportation and warehousing	1,380	2.7%	21,032	4.0%	2,479	12.0%	3,414	3.8%
Information	556	1.1%	7,270	1.4%	136	0.7%	592	0.7%
Finance and insurance	984	1.9%	21,055	4.0%	547	2.7%	2,315	2.6%
Real estate and rental and leasing	1,584	3.1%	25,467	4.8%	814	4.0%	2,878	3.2%
Professional, scientific, and technical services	3,466	6.7%	32,253	6.1%	659	3.2%	3,601	4.0%
Management of companies and enterprises	79	0.2%	2,197	0.4%	(D)	(D)	242	0.3%
Administrative & support & waste management & remediation services	2,971	5.8%	41,051	7.7%	(D)	(D)	5,557	6.2%
Educational services	802	1.6%	9,292	1.8%	190	0.9%	777	0.9%
Health care and social assistance	4,816	9.3%	71,265	13.4%	1,089	5.3%	9,151	10.1%
Arts, entertainment, and recreation	887	1.7%	12,245	2.3%	203	1.0%	705	0.8%
Accommodation and food services	3,889	7.5%	42,718	8.1%	1,610	7.8%	6,587	7.3%
Other services (except gov't & government enterprises)	2,761	5.3%	30,731	5.8%	1,073	5.2%	4,234	4.7%
Government and government enterprises	15,328	29.7%	90,676	17.1%	3,919	19.0%	18,685	20.7%
TOTAL	**51,642**	**100%**	**530,482**	**100%**	**20,575**	**100%**	**90,300**	**100%**

Source: Bureau of Economic Analysis (BEA), 2019.

When an industry has an LQ >1.00, in other words, is more specialized in production within that industry than the same industry at the national level, the industry is considered a basic industry. When the LQ > 1.25, the industry is assumed to be exporting goods and services outside of the region and therefore bringing outside money into the county economy. Tables 4-7 present the employment location quotients for each of the four Southern Arizona counties in 2019. Industries included within the bio- and circular economies are identified with an asterisk.

TABLE 4. TOP 10 PRIVATE INDUSTRIES IN COCHISE COUNTY BY EMPLOYMENT LQ, 2019

Industry	*LQ Employment*
NAICS 111335 Tree nut farming	29.96*
NAICS 111940 Hay farming	10.56*
NAICS 115115 Farm labor contractors and crew leaders	9.75*
NAICS 424520 Livestock merchant wholesalers	8.94
NAICS 488410 Motor vehicle towing	3.74
NAICS 561520 Tour operators	3.69
NAICS 312130 Wineries	3.68*
NAICS 444130 Hardware stores	3.56
NAICS 238131 Residential framing contractors	3.25
NAICS 562991 Septic tank and related services	3.15

Source: Bureau of Labor Statistics Quarterly Census of Employment and Wages (BLS QCEW), 2019.
* denotes sector is part of the bioeconomy or circular economy.

Of the top 10 most concentrated private industries in Cochise County, industries within the bioeconomy occupy four of the top 10 spots and three occupy the top three spots (Table 4). By 2019 employment LQs, Cochise County is specialized in tree nut farming, hay farming, farm labor contracting, and wineries. To put these results into perspective, the share of employment in tree nut farming is approximately 30 times higher in Cochise County than the national average. There are no circular economy industries within the top 10 most concentrated industries in Cochise County.

TABLE 5. TOP 10 PRIVATE INDUSTRIES IN PIMA COUNTY BY EMPLOYMENT LQ, 2019

Industry	*LQ Employment*
NAICS 213114 Support activities for metal mining	9.74
NAICS 561422 Telemarketing and other contact centers	7.47
NAICS 541713 Research and development in nanotechnology	6.93
NAICS 561330 Professional employer organizations	6.88
NAICS 611519 Other technical and trade schools	4.90
NAICS 488190 Other support activities for air transport.	4.62
NAICS 621493 Freestanding emergency medical centers	4.57
NAICS 811118 Other automotive mechanical and elec. Repair	3.94*
NAICS 451211 Book stores	3.70
NAICS 332322 Sheet metal work manufacturing	3.42

Source: Bureau of Labor Statistics Quarterly Census of Employment and Wages (BLS QCEW), 2019.
* denotes sector is part of the bioeconomy or circular economy.

The only bio- or circular economy industry that has an LQ in the top 10 for Pima County is automotive mechanical repair, a circular economy industry (Table 5). In 2019, Pima County had 4 times the national average employment within this industry. While outside of this study's definition of the bioeconomy, Pima County is specialized in R&D in nanotechnology, with employment nearly 7 times more concentrated than the national average.

Of the top 10 most concentrated private industries in Santa Cruz County, industries within the bioeconomy occupy three of the top 10 spots, including agricultural support services for postharvest crop activities, cattle ranching, and wineries (Table 6). Other industries in which Santa Cruz County is specialized in are in relation to the fresh produce industry cluster. There are no circular economy industries within the top 10 in Santa Cruz County.

TABLE 6. TOP 10 PRIVATE INDUSTRIES IN SANTA CRUZ COUNTY BY EMPLOYMENT LQ, 2019

Industry	*LQ Employment*
NAICS 424480 Fruit and vegetable merchant wholesalers	147.37
NAICS 493120 Refrigerated warehousing and storage	29.22
NAICS 445230 Fruit and vegetable markets	21.64
NAICS 115114 Other postharvest crop activities	20.26*
NAICS 488510 Freight transportation arrangement	18.65
NAICS 453920 Art dealers	16.59
NAICS 112111 Beef cattle ranching and farming	15.40*
NAICS 448150 Clothing accessories stores	8.81
NAICS 484230 Other specialized trucking, long-distance	5.56
NAICS 312130 Wineries	5.40*

Source: Bureau of Labor Statistics Quarterly Census of Employment and Wages (BLS QCEW), 2019.
* denotes sector is part of the bioeconomy or circular economy.

Eight (8) of the top 10 most concentrated private industries in Yuma County are industries within the bioeconomy, specifically within agricultural industries including the production of citrus, vegetables, and melons, as well as various types of agricultural support activities (Table 7). Yuma County's specialization in agricultural production is demonstrated by the magnitude of its employment location quotients. The share of employment for all of the top 10 industries suggests that Yuma County has employment in each of these industries at least 15 times higher than the national average and as high as 177 times the national average.

TABLE 7. TOP 10 PRIVATE INDUSTRIES IN YUMA COUNTY BY EMPLOYMENT LQ, 2019

Industry	*LQ Employment*
NAICS 111320 Citrus, except orange, groves	177.26*
NAICS 115113 Crop harvesting, primarily by machine	88.75*
NAICS 111219 Other vegetable and melon farming	81.08*
NAICS 115115 Farm labor contractors and crew leaders	67.83*
NAICS 115114 Other postharvest crop activities	45.38*
NAICS 115112 Soil preparation, planting, and cultivating	38.65*
NAICS 441210 Recreational vehicle dealers	28.65
NAICS 111940 Hay farming	24.30*
NAICS 111920 Cotton farming	18.98*
NAICS 721211 RV parks and campgrounds	16.05

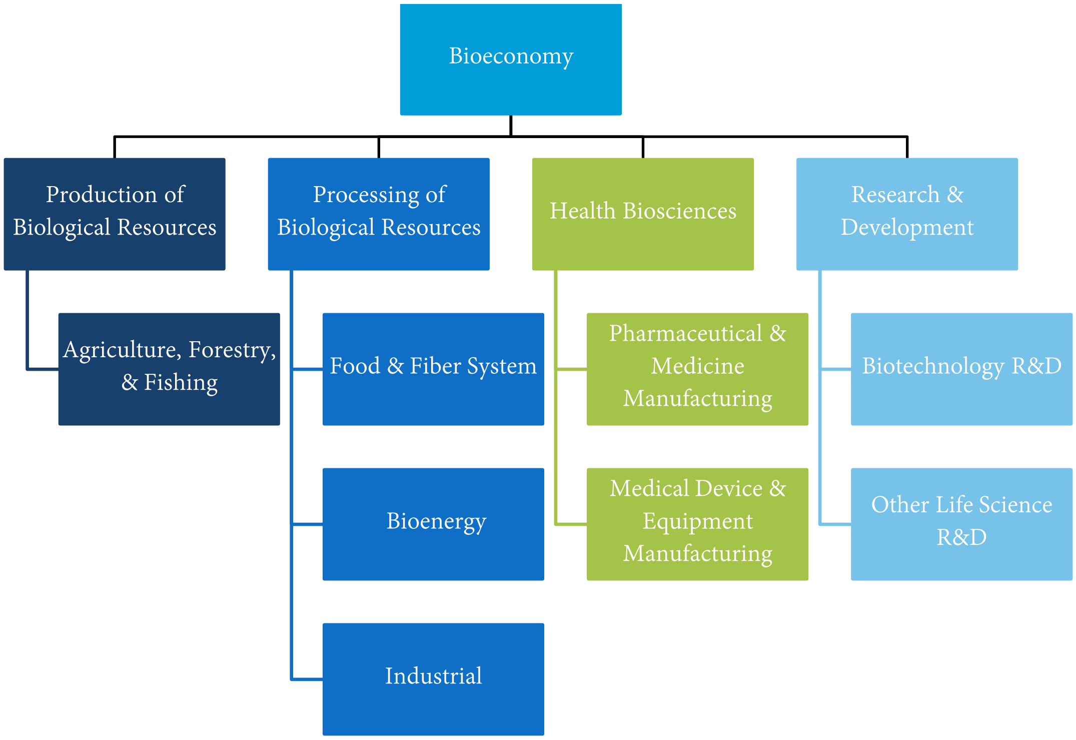
Source: Bureau of Labor Statistics Quarterly Census of Employment and Wages (BLS QCEW), 2019.
* denotes sector is part of the bioeconomy or circular economy.

To summarize, Southern Arizona includes a major urban area as well as outlying rural areas with specializations in different types of agricultural production.

4.2. Bioeconomy Landscape

The following section presents the ***bioeconomy*** landscape in Southern Arizona and presents industry statistics for 2019. For the purposes of the economic contribution analysis, bioeconomy industries are engaged in the: (1) Production of Biological Resources (plants, animals, micro-organisms), (2) Processing of Biological Resources, (3) Health Biosciences, and (4) Bio-based Private Sector Research and Development (Figure 5; see Table 1 for the complete list of industries and their corresponding NAICS codes and IMPLAN sectors). While private sector bio-based research and development is captured in the economic contribution analysis, little data is available to capture economic activity associated with breakthroughs and technological advancements enabled by ***research, innovation, and applications of biological and life sciences***. Section 6 provides illustrative case studies of how these advancements have application within bioeconomy industries.

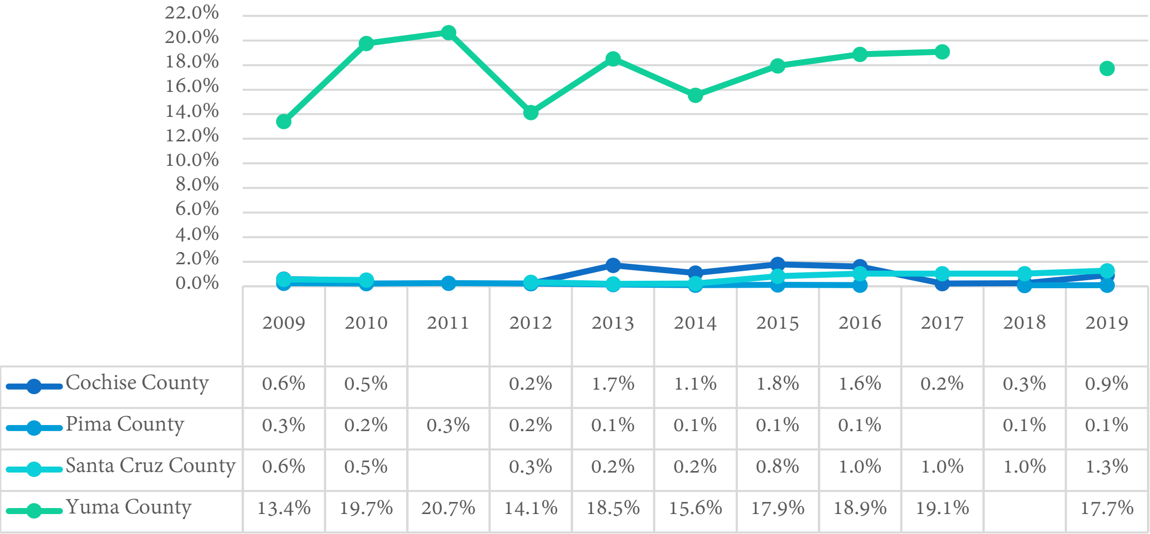
Figure 5. Southern Arizona Bioeconomy Components



4.2.1. Production of Biological Resources: Agriculture, Forestry, and Fishing

Industries that ***produce renewable biological resources*** are considered part of the bioeconomy and include ***agriculture, forestry, and fishing***. Within the NAICS framework, this includes all industries under the 2-digit NAICS Code 11- Agriculture, Forestry, Fishing, and Hunting, including NAICS 111, 112, 113, 114, and 115 (Table 1). Within Southern Arizona, production of biomass represents a small share of county-level GDP in Cochise, Pima, and Santa Cruz County, ranging from one-tenth of 1% in urban Pima County to just over 1% in Santa Cruz County in 2019 (Figure 6). In contrast, agriculture and its related activities account for more than 17% of the county GDP in Yuma (Figure 6).

FIGURE 6. AGRICULTURE, FORESTRY, FISHING AND HUNTING GDP AS PERCENT OF COUNTY GDP, 2009-2019



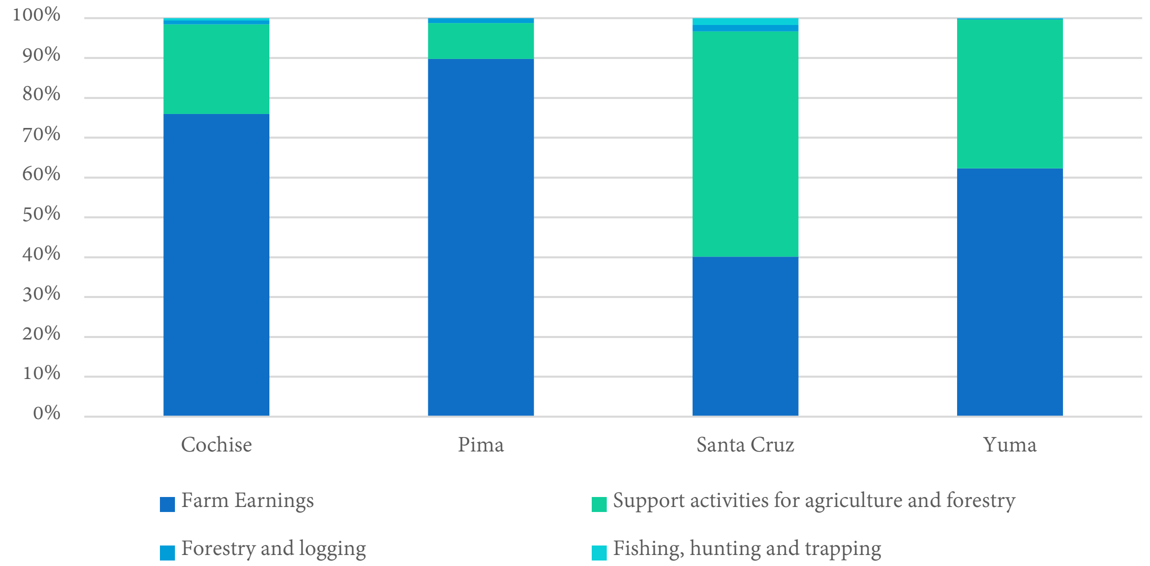
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Cochise County	0.6%	0.5%		0.2%	1.7%	1.1%	1.8%	1.6%	0.2%	0.3%	0.9%
Pima County	0.3%	0.2%	0.3%	0.2%	0.1%	0.1%	0.1%	0.1%		0.1%	0.1%
Santa Cruz County	0.6%	0.5%		0.3%	0.2%	0.2%	0.8%	1.0%	1.0%	1.0%	1.3%
Yuma County	13.4%	19.7%	20.7%	14.1%	18.5%	15.6%	17.9%	18.9%	19.1%		17.7%

Source: Bureau of Economic Analysis (BEA), 2021. Data last updated December 8, 2021.

Notes: Years without values are not available to avoid disclosure of confidential information.

A majority of this economic activity is related to traditional agricultural activities such as growing crops (NAICS 111) and raising livestock (NAICS 112) while very little is related to forestry (NAICS 113) and fishing and hunting (NAICS 114). There is significant economic activity in the agricultural support services industry (NAICS 115). This includes services such as soil preparation and planting as well as crop harvesting, farm labor contracting, cotton ginning, and breeding services within the livestock industry. Figure 7 presents the income distribution amongst agricultural sub-sectors, where on-farm earnings (related to both crop and livestock production) dominate.

FIGURE 7. INCOME DISTRIBUTION BY AGRICULTURAL SUB-SECTOR, 2019



Source: Bureau of Economic Analysis (BEA), 2021. Data last updated December 8, 2021.

Notes: Pima County & Santa Cruz County include values from 2016 (most recently available data) due to missing data for 2020.

Regionally, Southern Arizona accounts for 13% of farms, 16% of farmland, and 36% of the agricultural sales in Arizona (Table 8) (USDA, 2019). According to the USDA, a farm is any place where $1,000 or more of agricultural produces were produced and sold, or would have normally been sold in a given year (USDA, 2019). Within Southern Arizona, Cochise County has the highest number of farms and ranches and the greatest amount of land in farms, while Santa Cruz County has the lowest number of farms and lowest acreage in farms. The county with the highest production of agricultural commodities by sales is Yuma County, which accounted for 83% of Southern Arizona agricultural sales and 30% of agricultural sales statewide (Table 8). The discrepancy between land in farms and sales is due to the prevalence of ranchland in Cochise County versus highly productive farmland in high-value fruit and vegetable crops in Yuma County.

TABLE 8. FARMS, LAND IN FARMS, AND PERCENT OF REGIONAL AND STATE AGRICULTURAL SALES, 2017

County	Farms		Land in Farms (including ranchland)		Harvested Cropland		Sales	
	#	*% So. AZ*	*Acres (000)*	*% So. AZ*	*Acres (000)*	*% So. AZ*	*Sales ($ millions)*	*% So. AZ*
Cochise	1,083	45%	973	24%	87	28%	$145	10%
Pima	661	27%	2,618	65%	29	9%	$76	5%
Santa Cruz	219	9%	198	5%	1	0.3%	$20	1%
Yuma	456	19%	247	6%	194	62%	$1,143	83%
So. AZ Total	2,419	100%	4,036	100%	311	100%	$1,383	100%
Arizona Total	19,086		25,126		916		$3,852	
So. AZ as % of State Total	13%		16%		34%		36%	

Source: USDA, 2019.

Agriculture is not only an important economic activity within Yuma County relative to other industries in the county, but agricultural commodities produced in the county account for nearly one-third of agricultural sales in the state and 83% of agricultural sales in Southern Arizona (Figure 6 and Table 8). According to the 2017 Census of Agriculture, top crops produced in Yuma County include ***vegetables, melons, potatoes, and sweet potatoes*** ($782.3 million), ***fruit, tree nuts, and berries*** ($62.5 million), and ***hay and other crops*** ($50.2 million). In fact, Yuma County is the third-largest vegetable and melon producing county in the entire United States and is one of the nation's largest producers of winter vegetables, particularly leafy greens such as Romaine, iceberg, red leaf, and green leaf lettuce (Duval et al., 2021). While Yuma County would be considered a crop-dominant county by sales and data are not disclosed for the sale of cattle and calves, the county ranks as the second largest producer in the state for cattle and calves, falling between Pinal County ($283.2 million) and Maricopa County (sales not disclosed). According to the 2017 Census of Agriculture, Yuma County is home to 4 feedlots. Although cattle sales are not disclosed for Yuma and Maricopa counties, approximated sales are on the order of more than $200 million for each county.

Cochise County ranks second in sales of crops and livestock among Southern Arizona counties, accounting for 10% of the region's agricultural sales. Cochise County is neither crop- nor livestock-dominant and top agricultural products include ***fruit, tree nuts, and berries*** ($31.5 million), ***cattle and calves*** ($29.1 million), ***grains, oilseeds, dry beans and dry peas*** ($24.4 million), and ***hay and other crops*** ($19.6 million). Cochise County has become a center for fruit and tree nut production, ranking in the top 5% of counties nationally for its sales (Duval et al., 2021). Production of fruit and tree nuts centers around pecans, pistachios, and wine grapes, with acreage increasing significantly over the last five years. Cochise County is also home to two American Viticultural Areas (AVAs), or areas that have been designated and recognized as wine grape growing regions (Duval et al., 2021). These are the Willcox and Sonoita AVAs that are partially located within the county.

Pima County ranks third in crop and livestock sales among Southern Arizona counties, accounting for 5% of the region's agricultural sales. Pima County is considered a crop-dominant county, with top agricultural products including ***nursery, greenhouse, floriculture, and sod*** ($14.6 million), ***cotton and cottonseed*** ($10.6 million), and ***cattle and calves*** ($8.3 million). Pima County also ranks third in the state for sales of ***fruit, tree nuts, and berries***, but sales data are not disclosed. Agricultural products within the ***nursery, greenhouse, floriculture, and sod*** sector include nursery stock crops include ornamentals, shade trees, fruit and tree nut trees and plants, and vines as well as greenhouse vegetables and fresh cut herbs grown under glass or other production (USDA, 2019).

Finally, Santa Cruz County has historically been a livestock-dominant county but has seen an increase in crop production in recent years. According to the 2017 Census of Agriculture, Santa Cruz County accounts for 1% of Southern Arizona agriculture sales. Given the relatively small geographic footprint of the county and concerns about identification of individual operations, few data are disclosed in the Census of Agriculture. That said, top agricultural products include ***cattle and calves*** ($9.6 million) and ***nursery, greenhouse, floriculture, and sod*** (sales not disclosed, but ranked fifth in the state). Like its neighbor Cochise County, Santa Cruz County has an emerging wine industry with a portion of the Sonoita AVA located within the county and grape acreage increasing from 191 acres in 2012 to 229 acres in 2017 (USDA, 2019; Duval et al., 2021). As mentioned previously, although Santa Cruz County is not a major producer of crops, the county handles large volumes of imported produce from Mexico.

4.2.2. Processing of Biological Resources: Food and Fiber System, Bioenergy / Biofuels, Industrial

Industries that ***process or convert renewable biological resources into value added products*** are included in the study as part of the bioeconomy. This includes industries involved in: (1) food, beverage, and fiber manufacturing, (2) producing renewable energy through the use of bioenergy and biofuels, and (3) producing industrial products through chemical manufacturing.

4.2.2.1. Food and Fiber System

Industries involved in the food and fiber system include those in food, beverage, and tobacco manufacturing. Industries involved in food manufacturing (NAICS 311) "transform livestock and agricultural products into products for intermediate or final consumption" (Census, 2022). Industries involved in beverage and tobacco product manufacturing (NAICS 312) include establishments that manufacture nonalcoholic and alcoholic beverages, including ice manufacturing as well as establishments engaged in processing tobacco and manufacturing tobacco products (Table 9), which is not applicable to Arizona. Finally, we include fiber processing within the textile industry (NAICS 313), which transforms natural or synthetic fibers into products such as yarn or fabric that are subsequently used to manufacture other products (Census, 2022) (Table 10). While it would be desirable to focus primarily on biobased textiles, or textiles produced from plant-based fibers such as cotton, linen, or jute or animal-based fibers such as silk and wool, and plant-derived semi-synthetic fibers such as rayon or bamboo, these statistics are not available.

In Pima County, the county with the most establishments and highest employment levels in the four-county study area, food manufacturing activity includes bread and bakery product manufacturing (NAICS 31181) and tortilla manufacturing (NAICS 31183) (QCEW, 2019). In Cochise County, 2 of the 5 food manufacturing establishments in the county are involved in animal slaughtering and processing (NAICS 311611) and one is engaged in crushing oilseeds and tree nuts (NAICS 311224). In terms of beverage manufacturing, Cochise and Santa Cruz counties have a high concentration of wineries (NAICS 31213), Pima County has a high concentration of breweries (NAICS 31213) and soft drink and ice manufacturing (NAICS 31211) and Yuma County has a high concentration of soft drink and ice manufacturing (NAICS 31211) (QCEW, 2019).

Fiber processing for textile production is rare in Southern Arizona, with only 2 establishments reported. These are located in Santa Cruz and Yuma counties. No additional data is disclosed.

TABLE 9. SOUTHERN ARIZONA FOOD AND BEVERAGE MANUFACTURING INDUSTRY ESTABLISHMENT, EMPLOYMENT, AND TOTAL WAGES, 2019

Region	NAICS 311- Food			NAICS 312- Beverage and Tobacco Product		
	Establishments	*Employment*	*Wages ($1,000)*	*Establishments*	*Employment*	*Wages ($1,000)*
Arizona	293	15,476	$705,765	142	4,684	$227,304
Cochise	5	ND	ND	11	104	$3,333
Pima	34	666	$ 20,641	20	771	$29,970
Santa Cruz	5	15	$522	8	35	$840
Yuma	10	445	$20,150	3	100	$4,653
Southern Arizona Total	54	1,126	$41,312	42	1,010	$38,795

Source: BLS QCEW, 2019.

TABLE 10. SOUTHERN ARIZONA TEXTILE MILLS INDUSTRY ESTABLISHMENT, EMPLOYMENT, AND TOTAL WAGES, 2019

Region	NAICS 313- Textile Mills			
	Establishments	*Employment*	*Annual Average Wages*	*Total Annual Wages*
Arizona	16	180	14,448,225	$80,231
Cochise	-	-	-	-
Pima County	-	-	-	-
Santa Cruz	1	ND	ND	ND
Yuma	1	ND	ND	ND

Source: BLS QCEW, 2019. ND = not disclosed

4.2.2.2. Bioenergy

Bioenergy is defined as “renewable energy derived from biological sources, to be used for heat, electricity, or vehicle fuel” (USDA ERS, 2022). Resources used to produce bioenergy are collectively referred to as biomass and can include wastes (crop, food, and wood), dedicated agricultural crops (such as corn grain, oil and sugar crops, and sorghum), and microalgae (U.S. Department of Energy, 2022; Sands et al., 2017). While in some cases agricultural crops are grown specifically as a feedstock for bioenergy production, other sources of biomass are generated through the production and consumption of other marketable products, such crop and forest residues or food waste (Sands et al., 2017). Using biomass to produce energy for heat and electricity is called biopower while using biomass to produce liquid fuels is called biofuels.

Biofuels are a small but growing fuel source for the transportation system in the United States. Ethanol is the most significant biofuel in the U.S. According to bioenergy statistics from the USDA Economic Research Service, Arizona ranked 22nd in the nation for fuel ethanol production capacity, with the ability to produce 50 million gallons per year. As of 2020, Arizona did not report any fuel ethanol production (Table 11). As to be expected, fuel ethanol production and utilization rates are concentrated in the Midwest in states with significant corn production.

There is only one ethanol production facility (NAICS 325193) in the state, which is located in Pinal County, just north of Pima County, and outside the scope of the contribution analysis (QCEW, 2019). The facility began production in 2007 and has an annual production capacity of 50 million gallons, produced from roughly 18 million bushels of grain from both local producers and producers from the Midwest (Pinal Energy, 2013). Ethanol production results in two byproducts used in other Arizona industries: distiller's grain, used by dairies and feedlots, and CO2, that is captured and recycled for use in soft drink, dry ice, and hydroponic operations (Pinal Energy, 2013). Employment and wage data for this operation are not disclosed.

TABLE 11. FUEL ETHANOL PRODUCTION FACILITIES CAPACITY AND UTILIZATION RATES BY STATE, 2020

Rank	States	Nameplate capacity[1]	Operating capacity[2]	Capacity utilization rates[3]
				Ratio
1	Iowa	4,495	4,445	0.99
2	Nebraska	2,274	2,176	0.96
3	Illinois	1,887	1,718	0.91
4	Minnesota	1,308	1,266	0.97
5	Indiana	1,198	991	0.83
˅	˅	˅	˅	˅
22	Arizona	50	0	0.00
	U.S. Total	**16,924**	**16,005**	**0.95**

1 Rated volume of plant under normal operating conditions.

2 Volume of ethanol produced. Can exceed rated volume if normal operating hours are exceeded.

3 Calculated by dividing ethanol production by nameplate capacity.

Source: USDA, Economic Research Service using data from: Renewable Fuels Association, 2019 RFA Ethanol Industry Outlook.

Another alternative fuel for vehicles is biodiesel, manufactured from vegetable oils, animal fats, or recycled restaurant grease (Alternative Fuels Data Center, 2022). In 2019, Arizona ranked 30th in the nation for biodiesel capacity, with 1 plant reported in the state. Production capacity in Arizona is a reported 2 million gallons per year (Table 12). As of June 2022, there were five companies registered for commercial sales of biodiesel fuels in Arizona. Three are in Maricopa County, one in Yavapai County, and one in Pima County (U.S. Environmental Protection

Agency, 2022). Only the company in Pima County is included in this analysis. It was the first company in Arizona to receive EPA approval for biodiesel production in 2005 and it manufactures biodiesel from used cooking oil (Grecycle, 2022).

TABLE 12. BIODIESEL PRODUCTION CAPACITY BY STATE, 2019

		Number	Million gallons per year
Rank	**State**	**Plants**	**Production**
1	Iowa	10	445
2	Texas	8	375
3	Missouri	8	253
4	Illinois	5	162
5	Arkansas	3	115
˅	˅	˅	˅
30	Arizona	1	2
	U.S. Total	**88**	**2,459**

- = No data reported.

Totals may not equal the sum of components due to independent rounding. Number of producers is a count of plants with operable capacity during December 2019.

Sources: USDA, Economic Research Service using data from, U.S. Energy Information Administration, Form EIA-22M "Monthly Biodiesel Production Survey," U.S. Department of Energy, Energy Information Administration, Monthly Biodiesel Production Report. Updated October 2020.

In 2019, Arizona only had one establishment identified as a biomass electric power generation facility, though employment and wage data are not reported (BLS QCEW, 2019). A biomass electric generation facility uses biomass (e.g., wood, waste, alcohol fuels) to produce electricity (U.S. Census Bureau, 2022). This facility is not located within the study area and is therefore not included in the analysis.

4.2.2.3. Industrial

Industries that process biomass for industrial uses include those involved in manufacturing basic organic chemicals from biological resources. While ethyl alcohol or ethanol production (NAICS 325193) could fall under this industrial category, it has been included in the bioenergy section. There is only one establishment in Arizona that produces ethanol, and it is located in Pinal County. Other industries included in this section are engaged in manufacturing organic chemicals from crude, gum, and wood (NAICS 325194) or other organic chemicals such as enzyme proteins, fatty acids, and silicone (NAICS 325199) (U.S. Census Bureau, 2017). According to the Bureau of Labor Statistics' (BLS) Quarterly Census of Employment and Wages (QCEW) statistics, there are no operations that manufacture crude, gum, or wood chemicals (NAICS 325194) and five establishments that manufacture all other organic chemicals (NAICS 325199) (BLS QCEW, 2019). Four of the five establishments are located in Maricopa County and are out of the scope of this analysis. One is located in Yuma County, but no additional wage or employment information is provided by the QCEW.

Finally, this subsection also includes industries that manufacture pesticides, fertilizer, and other agricultural chemicals (NAICS 3253). These industries were not directly included in the NASEM bioeconomy landscape and are often excluded in EU studies (e.g. Ronzon et al., 2017; Ronzon and M'Barek, 2018). Yet Lier et al. (2018) report different European countries including portions of their chemical industries to varying degrees. Pesticides, fertilizer, and other agricultural chemical manufacturing is included in the "Bioscience" industry in the Southern Arizona Bioscience Roadmap. They call this "Agricultural Feedstock and Chemicals" and describes this subsector as applying "life science knowledge and biotechnologies to the processing of agricultural goods and production of organic and agricultural chemicals." Product examples include ethanol, fertilizers, pesticides, sustainable lubricants and oils, and food and feed additives" (Battelle, 2006).

Activities under this NAICS code involve fossil-fuel and inorganic chemical-based production, which is usually not associated with the bioeconomy (or circularity). Yet, it also includes firms manufacturing fertilizers from sewage or animal waste as well as firms that manufacture compost through controlled aerobic, biological decomposition and curing of biodegradable materials (U.S. Census Bureau, 2017). These activities rely directly on biological process (and also exhibit aspects of circularity). In addition, it can also include production of biopesticides, which are derived from natural materials such as animals, plants, bacteria, and minerals (U.S. EPA, 2023). Further, even if excluded from direct effects in economic contribution analysis, these activities would be captured in total contributions via indirect multiplier effects.

According to the QCEW, Arizona has 16 establishments engaged in this work (Table 13). Two of the four Southern Arizona counties report agricultural chemical manufacturing establishments, one in Cochise County and two in Yuma County. Additional wage and employment data are not disclosed (Table 13).

TABLE 13. ESTABLISHMENTS, EMPLOYMENT, AND WAGES IN PESTICIDE, FERTILIZER, AND OTHER AGRICULTURAL CHEMICAL MANUFACTURING (NAICS 3253) BY ARIZONA COUNTY, 2019

Region	Establishments	Employment	Wages
Arizona	16	601	$ 33,686,046
Cochise County	1	ND	ND
Yuma County	2	ND	ND

Source: BLS QCEW, 2019

4.2.3. Health Biosciences

Industries that ***use biological products and processes for health-related outcomes*** are also included in the bioeconomy in this study. This component includes industries that are involved in developing medicines, pharmaceutical products, diagnostic substances and products, as well as industries that are involved in producing equipment and instruments necessary to engage in medical diagnostic, evaluation, or treatment processes.

4.2.3.1. Pharmaceutical and Medicine Manufacturing

Industries that manufacture medicinal and pharmaceutical products (NAICS 3254) are engaged in preparing uncompounded medicinal chemicals, grading, grinding, and milling botanical drugs and herbs, manufacturing pharmaceutical products such as tablets, capsules, or solutions, manufacturing substances for diagnostic tests, or manufacturing other biological products such as vaccines (U.S. Census Bureau, 2017). Soejarto and Farnsworth

(1989) have estimated that roughly a quarter of prescription drugs contained some natural products, derived from plants and animals. In addition to providing raw materials for pharmaceuticals, natural products provide information for pharmaceutical development. Semi-synthesis isolates large, complex molecules from plants, animals, or bacteria to serve as building blocks to produce a wide range of medicines (Nicolaou, et al., 1996). The molecular structures of natural products serve as blueprints or as leads in developing compounds. Of the 1,394 small-molecule approved drugs worldwide from 1981 to 2019, 6% were natural products or natural product botanicals, 28% were derived from a natural product (often relying on semi-synthesis), and 31% were "natural product mimics" produced via total synthesis but whose molecular framework came from a natural product (Newman and Cragg, 2020). There are a total of 87 establishments in the state involved in pharmaceutical and medicine manufacturing (Table 14). Pima County is reported to have 5 establishments engaged in this work, but employment and wage data are not disclosed to avoid identifying individual operations. Three of the five establishments in Pima County are engaged in manufacturing pharmaceutical products for consumption in dose form such as tablets or capsules (BLS QCEW, 2019).

TABLE 14. ESTABLISHMENTS, EMPLOYMENT, AND WAGES IN PHARMACEUTICAL AND MEDICINE MANUFACTURING (NAICS 3254) BY ARIZONA COUNTY, 2019

Region	Establishments	Employment	Wages
Arizona	87	3,501	$ 217,598,812
Pima County	5	ND	ND

Source: BLS QCEW, 2019

4.2.3.2. Medical Device & Equipment Manufacturing

Industries that enable research, medical diagnostic, evaluation, or treatment processes through the manufacturing of medical device and equipment is also included within the bioeconomy. More specifically, these manufacturing industries include electromedical and electrotherapeutic apparatus manufacturing (NAICS 334510), analytical laboratory instrument manufacturing (NAICS 334516), irradiation apparatus manufacturing (NAICS 334517), and surgical and medical instrument manufacturing (NAICS 339112). The NASEM report includes these industries noting, "Some medical devices require the extensive use of newly developed biotechnologies and the most current biological research... Because all medical devices have life science R&D in their life cycle, their inclusion in the bioeconomy is warranted."

Medical devices and equipment are also grouped with biotechnology and other biological innovations in U.S. policies. The America Invents Act of 2011 (P.L. 112-29) groups medical devices with biotechnology and advanced manufacturing initiatives to speed the patent granting process. The U.S. inter-agency Coordinated Framework for the Regulation of Biotechnology addresses "The manufacture by the newer technologies [i.e., genetic engineering] of food, the development of new drugs, medical devices, biologics for humans and animals, and pesticides" together (OSTP, 1986). The Food and Drug Administration (FDA) regulates medical devices along with foods and pharmaceuticals as biological knowledge is required for all three.

Establishments within the electromedical and electrotherapeutic apparatus manufacturing industry (NAICS 334510) manufacture MRI equipment, ultrasound equipment, pacemakers, and any many other types of electromedical devices. The NASEM report notes, "Mass spectrometers are the workhorse instruments in the field of proteomics, an important field of life science." Establishments within the analytical laboratory instrument manufacturing industry (NAICS 334516) manufacture instruments for laboratories, specifically instruments for analyzing the chemical or physical composition or concentration of various materials. Another subset of medical device and equipment manufacturing involves producing irradiation scanners, devices, and equipment (NAICS334517), including CT scanners and X-ray equipment. Finally, the surgical and medical instrument manufacturing industry (NAICS 339112) includes all other medical manufacturing not included within the three previous subsectors. Among others, this includes establishments manufacturing “syringes, hypodermic needles, anesthesia apparatus, blood transfusion equipment, catheters, surgical clamps, and medical thermometers” (U.S. Census Bureau, 2017).

There are a total of 77 establishments in the state involved in medical device and equipment manufacturing. Pima County is reported to have 14 establishments engaged in this work (Table 15). Approximately half of Pima County’s medical and device equipment manufacturers are engaged in manufacturing analytical lab instruments (NAICS334516) (BLS QCEW, 2019). Santa Cruz County reported one establishment engaged in surgical and medical instrument manufacturing (BLS QCEW, 2019). As a lower bound (due to undisclosed data), there are at least 235 jobs supported with wages of approximately $11.0 million within this industry (Table 10).

TABLE 15. ESTABLISHMENTS, EMPLOYMENT, AND WAGES IN MEDICAL DEVICE AND EQUIPMENT MANUFACTURING (NAICS 334510, 334516, 334517, AND 339112) BY ARIZONA COUNTY, 2019

Region	Establishments	Employment	Wages
Arizona	77	4,581[1]	$ 401,481,526 [1]
Pima County	14	235[2]	$ 11,038,716[2]
Santa Cruz County	1	ND	ND

1 Employment and wage data at the state-level is not disclosed for NAICS 334517- Irradiation apparatus manufacturing.

2 Employment and wage data is only disclosed for NAICS 339112- Surgical and medical instrument manufacturing.

4.2.4. Bio-based Private Sector Research and Development

Finally, private industries that ***support and enhance the advancement of the bioeconomy through research and technological advances in biological sciences, engineering, and computing and information sciences*** are included in the study as part of the bioeconomy. This includes private businesses involved in research and development (R&D) in biotechnology (NAICS 541714) and research and development in the physical, engineering, and life sciences (NAICS 541715).

Biotechnology R&D involves “the study of the use of microorganisms and cellular and biomolecular processes to develop or alter living or non-living materials,” which may result in genetically altered products that can be used across a wide range of industries. Supporting the continued development of the bioeconomy, outside of biotechnology processes, is R&D in agricultural, environmental, chemical, computing, engineering, and information sciences, among others.

There are a total of 167 establishments in Arizona involved in biotechnology R&D (NAICS 541714). Pima County is reported to have 18 establishments, employing nearly 300 people and paying more than $28 million in wages

(Table 16). Cochise and Yuma counties each report 1 establishment, but employment and wage data are not disclosed to avoid identifying individual operations (BLS QCEW, 2019). Santa Cruz County does not report having this type of establishment.

Table 16. Establishments, Employment, and Wages In Biotechnology and Other Life Science R&D (NAICS 541714 & 541715) By Arizona County, 2019

Region	NAICS 541714- Biotechnology R&D			NAICS 541715- Other Life Science R&D		
	Establishments	*Employment*	*Wages ($1,000)*	*Establishments*	*Employment*	*Wages ($1,000)*
Arizona	167	1,535	$162,906	338	2,710	$258,665
Cochise	1	ND	ND	7	39	$3,668
Pima	18	292	$28,708	65	709	$60,996
Santa Cruz	-	-	-	1	ND	ND
Yuma	1	ND	ND	8	53	$2,765
Southern Arizona Total	**20**	**292**	**$28,708**	**81**	**801**	**$67,430**

A substantially larger number of establishments are engaged in other research and development in the physical, engineering, and life sciences in Southern Arizona. In 2019, there were a total of 81 establishments engaged in this work in the study region (Table 16). A large majority (80%) of these establishments are located in Pima County, which employed approximately 700 people and paid $61 million in wages. Yuma County reported having 8 establishments and employing 53 people, Cochise County reported having 7 establishments and employing 39 people, and Santa Cruz County reported 1 establishment, with no employment or wage data disclosed (Table 16).

4.2.5. Bioeconomy Summary

According to the Bureau of Labor Statistics’ QCEW statistics, there were a total of 614 establishments within the bioeconomy in Southern Arizona in 2019, most of which were involved in the production of biomass on Arizona’s farms and ranches (Table 17).

Table 17. Southern Arizona Establishment Count By Bioeconomy Component, 2019

Bioeconomy Components	Establishments	Cochise County	Pima County	Santa Cruz County	Yuma County
Production of Biomass[1]	391	62	61	27	241
Food and Fiber System[2]	98	16	54	14	14
Bioenergy[3]	0	0	0	0	0
Industrial[4]	4	1	0	0	3
Health Biosciences[5]	20	0	19	1	0
Research & Development[6]	101	8	83	1	9
Total Bioeconomy	**614**	87	217	43	267

Source: BLS QCEW, 2019; See more detailed descriptions of industries included in Table 1.

1 Industries involved in plant or animal production (NAICS 11).

2 Industries involved in food, beverage, and fiber manufacturing (NAICS 311, 312, 313, 3161).

3 Industries producing renewable energy through use of biomass (NAICS 221117, 325193).

4 Industries involved in manufacturing organic and agricultural chemicals (NAICS 325194, 325199, 3253).

5 Industries that use biological products and processes for health-related outcomes (NAICS 3254, 334510, 334516, 334517, 339112).

6 Industries that support the advancement of the bioeconomy through research and development in biotechnology (NAICS 541714) and physical, engineering, and life sciences (NAICS 541715).

Note, however, that the number of agricultural establishments is significantly lower than the number of Southern Arizona farms and ranches reported by the Census of Agriculture. This is due to the broad definition of a farm by the Census, whereby a farm is a place that has the capacity to produce $1,000 of agricultural product, and the fact that QCEW data only includes establishments that are subject to unemployment insurance (BLS QCEW, 2022). Bioeconomy establishments are located throughout Southern Arizona, though the largest number are in Yuma County, followed by Pima County. While Yuma County has a heavy concentration of biomass production, Pima County has a much higher concentration of research and development activities and food and fiber production (Table 17). When measured by the number of jobs, production of biomass in Yuma County represents a large share of total bioeconomy employment in the region (Table 18).

Table 18. Southern Arizona Bioeconomy Jobs*, 2019

County	So. AZ	Cochise County	Pima County	Santa Cruz County	Yuma County
Production of Biomass	14,069	958	572	0	12,539
Food and Fiber System	2,136	104	1,437	50	545
Bioenergy	0	0	0	0	0
Industrial	0	0	0	0	0
Health Biosciences	235	0	235	0	0
Research and Development	1,093	39	1,001	0	53
Total	17,533	1,101	3,245	50	13,137

Source: BLS QCEW, 2019

* Jobs reflect data reported by QCEW. QCEW does not report data when such reporting could reveal the identity of cooperating employers. QCEW data also excludes proprietors, the unincorporated self-employed, unpaid family members, and certain farm and domestic workers. Therefore, jobs presented here represents a lower bound.

4.3. Circular Economy Landscape

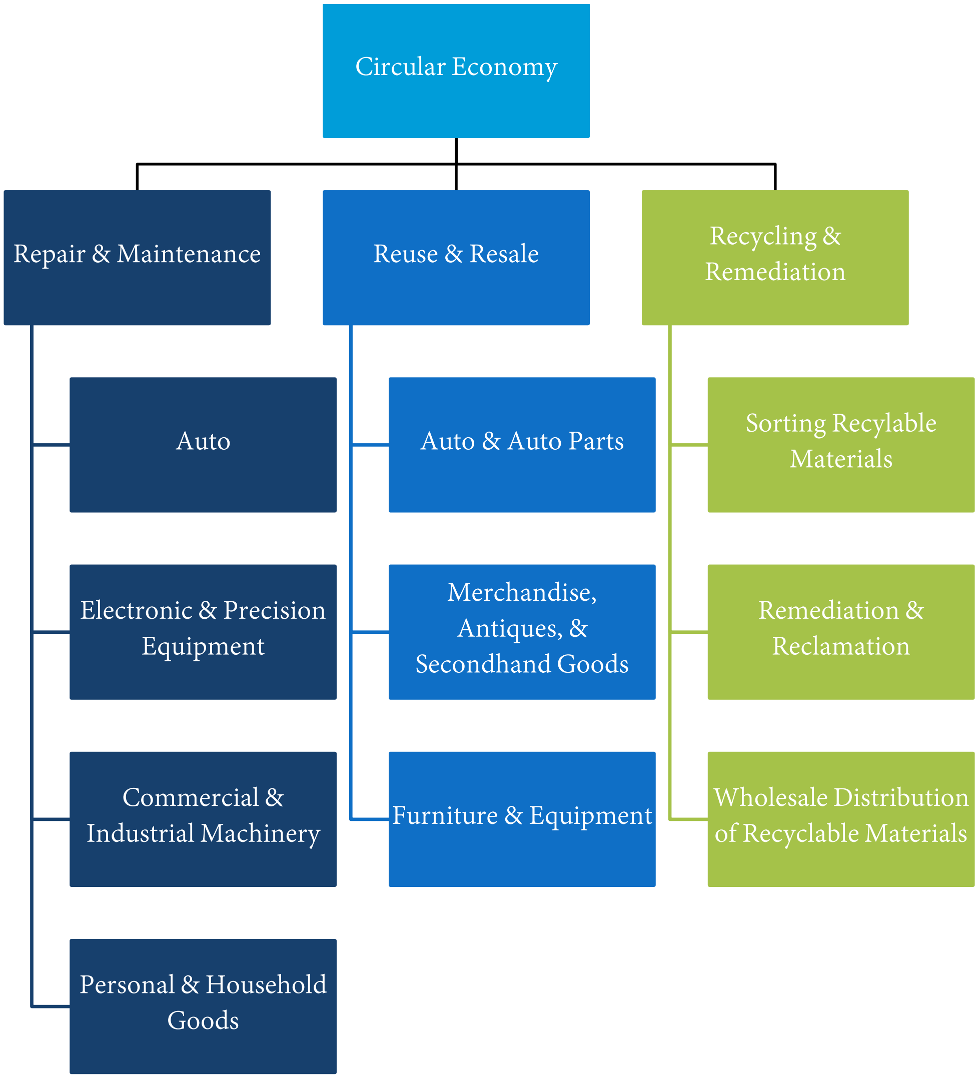
A circular economy focuses on minimizing waste and optimizing resources use through reuse, sharing, repair, refurbishment, remanufacturing, and recycling. The circular economy includes industries that extend the life of existing products or materials for one user, another user, or that recover specific materials for a new product. More specifically, the circular economy includes industries that are involved in: (1) Repair and Maintenance, (2) Reuse and Resale, and (3) Recycling and Remediation (Figure 8). These industries (identified by their NAICS codes) fit within the circular economy using the strictest definition of the circular economy in that they are engaged in those activities as their primary business model and source of sales. While *circular industries* are captured in the economic contribution analysis, little to no data is available to capture economic activity associated with *circular activities* within industries. Section 6 provides illustrative case studies of how circularity has been introduced or could be introduced within bioeconomy industries.

4.3.1. Repair and Maintenance

Industries that ***extend the life of existing products or materials for one user*** are considered a part of the circular economy and include repair and maintenance industries across various products and uses. Within the NAICS framework this includes automotive repair and maintenance, not including car washes (NAICS 8111 less NAICS 811192), electronic and precision equipment repair and maintenance (NAICS 8112), commercial and industrial machinery repair and maintenance (NAICS 8113), and personal and household goods repair and maintenance (NAICS 8114).

There are a total of 4,733 establishments in Arizona involved in repair and maintenance activities (Table 18). Pima County is reported to have 653 repair and maintenance establishments, employing more than 3,800 people, a majority of which work in automotive repair and maintenance (BLS QCEW, 2019). Yuma County has approximately 150 establishments that engage in this work, supporting nearly 900 jobs and $39 million in wages. Most repair and maintenance employment in Yuma is also related to auto repair and maintenance, though nearly one-fourth is in commercial and industrial machinery repair and maintenance (BLS QCEW, 2019). Cochise and Santa Cruz counties have 64 and 20 repair and maintenance establishments, respectively, but not all wage and employment data are disclosed. Therefore, employment and wage data for these counties represent a lower bound.

Figure 8. Southern Arizona Circular Economy Components



In total there were 886 establishments engaged in repair and maintenance in Southern Arizona, employing more than 4,700 and paying more than $200 million in wages (Table 19). As mentioned previously, these employment and wage estimates are a lower bound estimate due to non-disclosure in Cochise and Santa Cruz counties.

TABLE 19. ESTABLISHMENTS, EMPLOYMENT, AND WAGES IN REPAIR AND MAINTENANCE[1] INDUSTRIES IN SOUTHERN ARIZONA BY COUNTY, 2019

Region	Establishments	Employment	Total Annual Wages ($1,000)
Arizona	4,733	28,689	$1,507,697
Cochise County	64	22[2]	$795[2]
Pima County	653	3,831	170,148
Santa Cruz County	20	20[2]	$1,437[2]
Yuma County	149	896	$39,070
Southern Arizona Total	886	4,769	$211,452

Source: BLS QCEW, 2019

1 Industries engaged in repair and maintenance include: NAICS 8111 (not including NAICS 811192), NAICS 8112, NAICS 8113, and NAICS 8114.

2 Employment and wage data is not disclosed in Cochise and Santa Cruz counties for automotive repair and maintenance, not including car washes (NAICS 8111 less NAICS 811192).

4.3.2. Reuse and Resale

Industries that ***extend the life of existing products or materials for another user*** are considered a part of the circular economy and include establishments engaged in the sale of used goods, either within a wholesale or retail establishment. Within the NAICS framework this includes establishments that are engaged in the wholesale distribution of used motor vehicle parts (NAICS 423140); the retail sale of used cars, trucks, and other vehicles (NAICS 441120); the retail sale of used merchandise, antiques, and secondhand goods (NAICS 453310); or the distribution of used household and office furniture and equipment (NAICS 484210).

TABLE 20. ESTABLISHMENTS, EMPLOYMENT, AND WAGES IN REUSE AND RESALE[1] INDUSTRIES IN SOUTHERN ARIZONA BY COUNTY, 2019

Region	Establishments	Employment[2]	Total Annual Wages ($1,000) [2]
Arizona	913	14,581	$ 585,804
Cochise County	25	141	$ 2,794
Pima County	149	1,798	$ 68,145
Santa Cruz County	8	ND	$ ND
Yuma County	24	89	$ 2,706
Southern Arizona Total	206	2,028	$ 211,452

Source: BLS QCEW, 2019

1 Industries engaged in the resale of used goods include: NAICS 423140, NAICS 441120, NAICS 453310, and NAICS 484210.

2 Employment and wage data is not disclosed (ND) in any Southern Arizona county for wholesale distribution of used motor vehicle parts (NAICS 423140), in Santa Cruz County for used car sales (NAICS 441120) and other used merchandise sales (NAICS 453310), and in Yuma County for used household and furniture equipment sales (NAICS 484210).

In Arizona, there are just over 14,500 people employed in industries that are engaged in the sale of used goods (Table 20). Pima County has almost 150 establishments, employing nearly 1,800 people. Approximately half of the jobs in Pima County are related to sales of secondhand goods, one-third are related to used car sales, and nearly one-fifth are related to the distribution of used household and office furniture and equipment (BLS QCEW, 2019). Employment and wage data for wholesale distribution of used motor vehicle parts are not available for Pima County or any of the other Southern Arizona counties.

Due to data non-disclosures, a lower bound estimate for employment and wages in industries that promote reuse in Southern Arizona is just over 2,000 jobs paying approximately $200 million in wages. This originates from 206 establishments engaged in this work.

4.3.3. Recycling and Remediation

Finally, industries that ***recover specific materials for a new product or are involved in remediation and other waste management services*** are considered a part of the circular economy. This includes establishments engaged in remediation and reclamation activities (NAICS 562910), establishments engaged separation and sorting recyclable materials from nonhazardous waste streams (NAICS 562920), and the wholesale distribution of recyclable materials, including automotive and industrial scrap (NAICS 423930).

In Southern Arizona, approximately 30 establishments are engaged in materials recovery and remediation and reclamation activities, the majority of which are located in Pima County (Table 21). Most employment and wage data are not disclosed for this cluster of industries to prevent identification of individual operations. The only industry in Southern Arizona with data disclosed is the industry involved in wholesale distribution of recyclable materials in Pima County. Pima County has 14 establishments engaged in this work, employing more than 150 people and with nearly $7 million in wages (BLS QCEW, 2019). Due to data disclosures, a lower bound estimate for employment and wages in industries that promote recovery and recycling of products in Southern Arizona is just over 150 jobs paying approximately $7 million in wages.

TABLE 21. ESTABLISHMENTS, EMPLOYMENT, AND WAGES IN RECYCLING AND REMEDIATION[1] INDUSTRIES IN SOUTHERN ARIZONA BY COUNTY, 2019

Region	Establishments	Employment[2]	Total Annual Wages ($1,000)[2]
Arizona	246	2,427	$ 122,447
Cochise County	3	ND	ND
Pima County	24	152	$ 6,889
Santa Cruz County	2	ND	ND
Yuma County	3	ND	ND
Southern Arizona Total	32	152	$ 6,889

Source: BLS QCEW, 2019

1 Industries engaged in recycling, remediation, or reclamation activities include: NAICS 562910, NAICS 562920, and NAICS 423930.

2 Employment and wage data is not disclosed (ND) in any Southern Arizona county for almost all recycling and remediation industries in Southern Arizona. Only Pima County discloses employment and wage data for industries involved in the distribution of recyclable materials (NAICS 423930).

4.3.4. Circular Economy Summary

According to the Bureau of Labor Statistics' QCEW statistics, there were 946 circular economy establishments in 2019, most of which were repair and maintenance operations (Table 22). The geographic concentration of establishments within the circular economy demonstrates a different pattern from bioeconomy establishments. Establishments are most numerous in Pima County and are dominated by repair and maintenance establishments.

TABLE 22. SOUTHERN ARIZONA ESTABLISHMENT COUNT BY BIOECONOMY AND CIRCULAR ECONOMY COMPONENT, 2019

Circular Economy Components	Establishments	Cochise County	Pima County	Santa Cruz County	Yuma County
Repair & Maintenance[1]	708	55	523	16	114
Reuse & Resale[2]	206	25	149	8	24
Recycling & Remediation[3]	32	3	24	2	3
Total Circular Economy	946	83	696	26	141

Source: BLS QCEW, 2019; See more detailed descriptions of industries included in Table 2.

1 Industries engaged in repair and maintenance include: NAICS 8111 (not including NAICS 811192), NAICS 8112, NAICS 8113, and NAICS 8114.

2 Industries engaged in the resale of used goods include: NAICS 423140, NAICS 441120, NAICS 453310, and NAICS 484210.

3 Industries engaged in recycling, remediation or reclamation activities include: NAICS 562910, NAICS 562920, and NAICS 423930.

This pattern more closely mirrors population in these counties versus agricultural production. Most jobs in the region's circular economy are located in Pima County, and again in the repair and maintenance sector (Table 23).

TABLE 23. CIRCULAR ECONOMY EMPLOYMENT IN SOUTHERN ARIZONA COUNTIES

Industry	So. AZ	Cochise County	Pima County	Santa Cruz County	Yuma County
Repair and Maintenance	3,995	191	3,096	57	651
Reuse	2,028	141	1,798	0	89
Recycling and Remediation	152	0	152	0	0
Total	6,175	332	5,046	57	740

Source: BLS QCEW, 2019

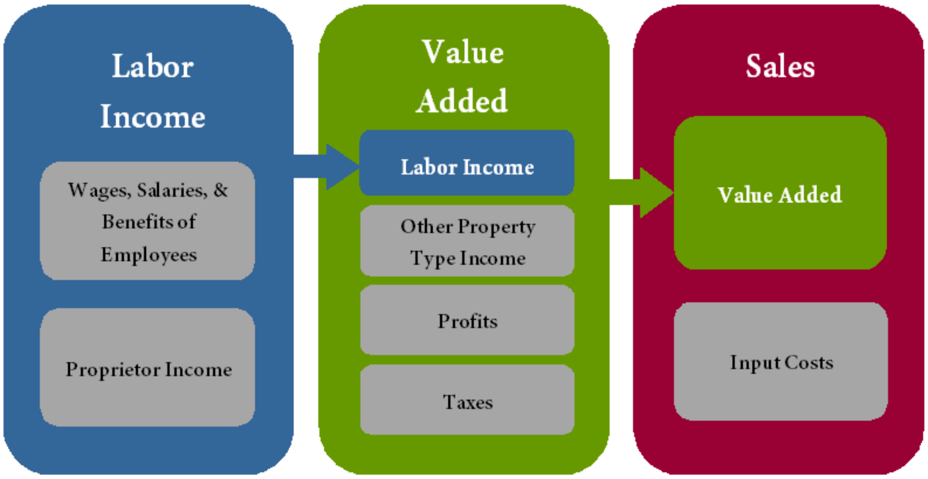
* Jobs reflect data reported by QCEW. QCEW does not report data when such reporting could reveal the identity of cooperating employers. QCEW data also excludes proprietors, the unincorporated self-employed, unpaid family members, and certain farm and domestic workers. Therefore, jobs presented here represents a lower bound.

5. Economic Contribution Analysis Results

The following section presents the economic contributions of the bio- and circular economies in Southern Arizona. This includes the direct economic activity supported by the bioeconomy and circular economy, including results for each industry group, as well as the total economic contribution, including indirect and induced multiplier effects. Economic contributions are presented using a variety of metrics including output (sales), value added, labor income, and jobs. These metrics are related to one another and cannot be combined. Figure 9 presents the relationship between output, value added, and labor income.

Output is perhaps the most intuitive to understand as it measures the total value of sales taking place in the regional economy and represents the flow of money throughout the region. This is a gross measure of economic activity in that it counts each additional change of hands as a "sale" and the total value of sales includes all of the expenses that were spent to produce the good or service plus the mark-up or the profits that are ultimately generated by the sale of the item to consumers. While *output* or *sales* is easy to understand, it double counts the sales value of inputs that are produced locally. For example, a farm product is counted as a "sale" when the farmer sells the product to a processor, wholesaler, or retail establishment. For those establishments, the money spent on the farm product is considered an input expense. Once the product is sold to the consumer, however, the value of the sale to the consumer is equal to the value of the inputs expended plus any profits. Therefore, the product's output or sales value is counted twice: once at the farm-gate and once when being sold to the consumer. *Value Added* is a component of output and is a metric that avoids this double counting by capturing only the value over and above the cost of inputs. At the national-level, value added is synonymous with Gross Domestic Product (GDP) and is a measure of a region's productivity. Value added includes labor income, profits, and taxes. *Labor income* is a component of value added and includes wages, salaries, and benefits to employees as well as proprietor or business-owner income. Finally, the economic contribution of an industry can be measured in terms of the number of full- and part-time *jobs* that it supports.

FIGURE 9. RELATIONSHIP BETWEEN ECONOMIC CONTRIBUTION METRICS



This section also identifies industries with (a) high sales supplying goods and services to the bio- and circular economies and (b) lower Regional Purchasing Coefficients (which measure the share of these goods and service sourced locally). With local expansion of these industries, bio- and circular economy businesses could shift from purchasing from suppliers outside of Southern Arizona to new or expanded suppliers inside the region. This "import substitution" strategy could increase the share of dollars staying within Southern Arizona.

5.1. Direct Economic Contributions of the Bioeconomy and Circular Economy to Southern Arizona

Economic activity directly attributable to the bioeconomy and the circular economy in Southern Arizona includes economic activity in several different industries. This study aggregates economic sectors of ***bioeconomy*** into four major components: (1) Production of Biomass, (2) Processing of Biomass, (3) Health Biosciences, and (4) Research and Development (see Table 1 for the complete list of industries and their corresponding NAICS codes and IMPLAN sectors). The ***circular economy*** is comprised of three major components: (1) Repair and Maintenance, (2) Reuse and Resale, and (3) Recycling and Remediation (see Table 2 for the complete list of industries and their corresponding NAICS codes and IMPLAN sectors).

5.1.1. Direct Economic Contributions of Bioeconomy

In 2019, the ***bioeconomy*** was estimated to directly account for an estimated more than 30,000 jobs in Southern Arizona (Table 22). Direct industry output or sales was an estimated $4.3 billion, and the bioeconomy directly contributed $1.7 billion to the gross regional product (Table 22). The largest component of the bioeconomy in Southern Arizona is comprised of industries involved in the production of biomass in the region's farms and ranches, accounting for approximately 80% of bioeconomy jobs and labor income, 75% of the value added attributed directly to the bioeconomy, and 60% of sales. A key driver of the $2.6 billion in sales is crop production in Yuma County, with nearly $1.5 billion in crop cash receipts in 2019.

The second largest component of the bioeconomy in Southern Arizona are industries involved in processing biomass. In 2019, these industries employed approximately 2,700 full- and part-time workers, contributed $180.1 million to the gross regional product, and had an estimated $1.1 billion in sales (Table 24). Economic activity within this component of the economy is split almost equally between food manufacturing and beverage manufacturing, including wineries, breweries, and distilleries.

Private-sector research and development in biotechnology and physical, engineering, and life sciences supported approximately 1,100 jobs, $172.1 million in value added, and $312 million in output or sales (Table 22). Most of the establishments and jobs in Southern Arizona related to bioeconomy-related research and development are involved in R&D in physical, engineering, and life sciences as opposed to biotechnology. Again, much of this economic activity takes place in Pima County, the region's most populous county.

Finally, health biosciences manufacturing (not including patient care) supported approximately 700 jobs, $65.1 million in value added, and $264.4 million in sales (Table 24). Most economic activity within this component includes manufacturing laboratory instruments as well as surgical and medical instruments. Like the private-sector R&D component of the bioeconomy, much of this manufacturing takes places in Pima County.

5.1.2. Direct Economic Contributions of Circular Economy

In 2019, the ***circular economy*** directly contributed to the Southern Arizona economy by providing 8,700 full- and part-time jobs and contributing $584.2 million to the Gross Regional Product (GRP) (Table 24). Direct industry output or sales was an estimated $792.7 million, with most sales originating from economic activities related to repair and maintenance.

Repair and maintenance accounts for approximately 60% of employment, two-thirds of labor income, and approximately 70% of sales within the circular economy. Industries that engage in repair and maintenance activities support 5,400 jobs and contribute approximately $366.6 million to GRP. Most economic activity in this component of the circular economy is related to automotive repair and maintenance.

Employing approximately 3,000 full- and part-time workers, the reuse and resale component of the circular economy contributed approximately$178 million to GRP. Many of the jobs within this component are with establishments that sell secondhand goods and used cars. The recycling and remediation component is the smallest subsector, supporting approximately 300 jobs and $39.5 million to GRP.

5.2. Total Economic Contributions, Including Multiplier Effects

5.2.1. Total Contribution of the Bioeconomy to Southern Arizona

By purchasing inputs from other businesses and employing people within Southern Arizona (who subsequently spend some of their income locally), the bioeconomy supports economic activity in other industries within the region. The economic activity supported through indirect effects, or business-to-business transactions, were an estimated $1.1 billion in sales, $505.6 million in value added, and 6,200 full- and part-time jobs (Table 24).

TABLE 24. DIRECT ECONOMIC CONTRIBUTION OF BIO- AND CIRCULAR ECONOMIES BY INDUSTRY GROUP IN SOUTHERN ARIZONA, 2019

Industry Category	Employment	Labor Income	Value Added	Output
Bioeconomy				
Production of Biomass	16,900	$1,121,446,400	$1,286,658,600	$2,607,113,200
Processing Biomass	2,700	$109,953,300	$180,668,600	$1,073,821,900
Health Biosciences	700	$30,315,400	$65,051,100	$264,632,800
Research & Development	1,100	$115,757,400	$172,143,300	$312,248,400
Total Direct Contribution	21,400	$1,377,472,500	$1,704,521,600	$4,257,816,300
Circular Economy				
Repair & Maintenance	5,400	$305,754,600	$366,571,400	$551,101,300
Reuse	3,000	$126,180,500	$178,154,600	$167,929,800
Recycling & Remediation	300	$21,546,300	$39,453,200	$73,625,400
Total Direct Contribution	8,700	$453,481,400	$584,178,900	$792,656,500
Total Direct Contributions	30,100	$1,830,953,900	$2,288,700,500	$5,050,472,800

Source: Authors' calculations using data from BLS QCEW, 2019; BEA, 2019b; IMPLAN, 2018.

Top industries that provide inputs to the businesses within the bioeconomy are real estate, wholesalers-specifically grocery and other nondurable good wholesalers, logistics and transportation, and other business services such as insurance and employment services (Table 25). Table 25 presents the top 10 industries in Southern Arizona that are supported through indirect effects associated with the bioeconomy as well as the regional purchase coefficients (RPCs) for each industry. Regional purchase coefficients represent that share of local demand that is met by local suppliers. A lower RPC represents an industry that could be targeted by economic development strategies to increase the share of dollars staying within the regional economy. This is called import substitution and would involve the bioeconomy shifting its purchasing from suppliers outside of Southern Arizona to new or expanded suppliers inside the region. Potential industries to target for growth to support and enhance the bioeconomy are the wholesaling industry, insurance industry, and scientific research and development services (Table 25). Additional economic activity is supported through induced effects, or when people employed within the bioeconomy spend their earnings on a variety of household goods and services within Southern Arizona.

TABLE 25. TOP 10 INDUSTRIES IN SOUTHERN ARIZONA SUPPORTED BY BIOECONOMY INDIRECT EFFECTS, 2019

Industry	Output / Sales	Regional Purchase Coefficient
Other real estate	$244,871,100	96.3%
Wholesale - Other nondurable goods merchant wholesalers	$96,486,600	62.1%
Wholesale - Grocery and related product wholesalers	$59,003,200	89.1%
Truck transportation	$52,630,800	84.8%
Electric power transmission and distribution	$41,576,400	92.5%
Insurance carriers, except direct life	$37,762,200	69.4%
Other local government enterprises	$35,425,800	99.9%
Scientific research and development services	$24,824,100	66.4%
Employment services	$23,365,200	85.2%
Wholesale - Machinery, equipment, and supplies	$22,671,900	71.3%

Source: Authors' calculations using data from BLS QCEW, 2019; BEA, 2019b; IMPLAN, 2018.

This spending supported an estimated $1.2 billion in sales, $684.2 million in value added, and 8,800 full- and part-time jobs (Table 26). Top industries supported through induced effects include hospitals and other healthcare providers, real estate including payments for mortgages, restaurants, and retail. Including direct, indirect, and induced multiplier effects, the total contribution of the bioeconomy to Southern Arizona in 2019 is more than $6.5 billion in sales. This level of sales supported 36,400 full- and part-time jobs and more than $2.0 billion in labor income. The total contribution of the bioeconomy to the Southern Arizona GRP in 2019 was an estimated $2.9 billion (Table 26).

TABLE 26. TOTAL CONTRIBUTION OF BIOECONOMY TO SOUTHERN ARIZONA, INCLUDING MULTIPLIER EFFECTS, 2019

Impact Type	Employment	Labor Income	Value Added	Output
Direct Effect	21,400	$1,377,472,500	$1,704,521,600	$4,257,816,300
Indirect Effect	6,200	$289,804,900	$505,611,500	$1,075,097,600
Induced Effect	8,800	$367,760,900	$684,224,700	$1,217,975,100
Total Effect	36,400	$2,035,038,300	$2,894,357,800	$6,550,889,000

Source: Authors' calculations using data from BLS QCEW, 2019; BEA, 2019b; IMPLAN, 2018.

5.2.2 Total Contribution of the Circular Economy to Southern Arizona

Similarly, the circular economy supports economic activity in other Southern Arizona industries through indirect and induced multiplier effects. The economic activity supported through indirect effects were an estimated $174.7 million in sales, $85.9 million in value added, and 1,200 full- and part-time jobs (Table 26). Top industries that provide inputs to the businesses within the circular economy are real estate, auto and auto part wholesalers and retailers, wholesalers of machinery and equipment, and other business services such as employment services, insurance, electricity, and delivery services (Table 27). Potential industries to target for growth to support and enhance the circular economy are the wholesaling industry, insurance industry, and warehousing and storage.

Top industries supported through induced multiplier effects are similar to those supported by the bioeconomy (hospitals and other healthcare providers, real estate including payments for mortgages, restaurants, and retail) are an estimated $368.6 million in sales, $207.1 million in value added, and 2,700 full- and part-time jobs (Table 28).

TABLE 27. TOP 10 INDUSTRIES IN SOUTHERN ARIZONA SUPPORTED BY CIRCULAR ECONOMY INDIRECT EFFECTS, 2019

Industry	Output	RPC
Other real estate	$37,430,554	96.3%
Employment services	$8,582,572	85.2%
Retail - Motor vehicle and parts dealers	$7,777,253	98.3%
Scenic and sightseeing transportation and support activities for transportation	$6,680,934	99.1%
Insurance carriers, except direct life	$5,737,152	69.4%
Wholesale - Motor vehicle and motor vehicle parts and supplies	$5,410,923	68.5%
Electric power transmission and distribution	$5,006,780	92.5%
Wholesale - Machinery, equipment, and supplies	$4,517,629	71.3%
Warehousing and storage	$4,164,875	66.4%
Couriers and messengers	$3,936,138	90.3%

Source: Authors' calculations using data from BLS QCEW, 2019; BEA, 2019b; IMPLAN, 2018.

Including direct, indirect, and induced multiplier effects, the total contribution of the circular economy to Southern Arizona in 2019 is 12,600 full- and part-time jobs, more than $600 million in labor income, and approximately $1.3 billion in sales. The total contribution of the circular economy to the Southern Arizona GRP in 2019 was a nearly $0.9 billion (Table 28).

Table 28. Total Contribution of Circular Economy to Southern Arizona, Including Multiplier Effects, 2019

Impact Type	Employment	Labor Income	Value Added	Output
Direct Effect	8,700	$453,481,400	$584,178,900	$792,656,500
Indirect Effect	1,200	$52,001,100	$85,897,400	$174,692,400
Induced Effect	2,700	$111,280,200	$207,063,900	$368,579,400
Total Effect	12,600	$616,762,700	$877,140,200	$1,335,928,300

Source: Authors' calculations using data from BLS QCEW, 2019; BEA, 2019b; IMPLAN, 2018.

5.2.3. Total Contributions of the Bio- and Circular Economies to Southern Arizona

Combined, the bioeconomy and the circular economy directly supported approximately 30,100 full- and part-time jobs and $2.3 billion in employee and business-owner income, resulting in a contribution of nearly $2.3 billion to the Southern Arizona GRP in 2019 (Table 29). Direct industry output or sales for the bio- and circular economies, combined, was an estimated $5.1 billion.

Including direct, indirect, and induced multiplier effects, the total contribution of the bio- and circular economies to the Southern Arizona economy in 2019 was an estimated $7.9 billion in sales. This level of sales supported a total of 49,000 full- and part-time jobs and more than $2.6 billion in labor income. The total contribution of the bio- and circular economies to the Southern Arizona GRP in 2019 was an estimated $3.8 billion (Table 29).

Table 29. Total Economic Contribution of Bio- and Circular Economies, Including Multiplier Effects, 2019

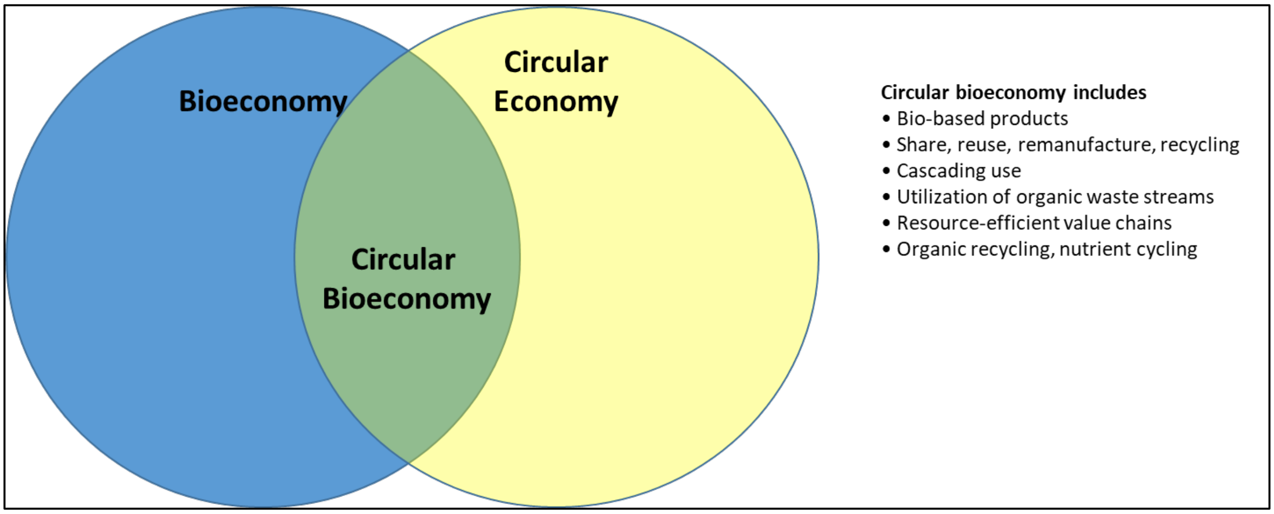
Impact Type	Employment	Labor Income	Value Added	Output
Direct Effect	30,100	$1,830,953,900	$2,288,700,500	$5,050,472,900
Indirect Effect	7,400	$341,806,000	$591,508,900	$1,249,790,000
Induced Effect	11,500	$479,041,100	$891,288,600	$1,586,554,500
Total Effect	49,000	$2,651,801,000	$3,771,498,000	$7,886,817,400

Source: Authors' calculations using data from BLS QCEW, 2019; BEA, 2019b; IMPLAN, 2018.

6. Bioeconomy and Circular Bioeconomy Case Studies

The final section of this study, presented as case studies, identifies and explores research and innovative efforts to grow the bioeconomy and circular bioeconomy in Southern Arizona. The case studies illustrate what Reichert (2019) calls the "new centrality" of universities in the innovation ecosystems where they operate. More importantly, these case studies help to highlight efforts that are taking place at the ***intersection*** of the bioeconomy and circular economy. While this report has focused on the union of the bioeconomy and the circular economy Carus and Dammer (2018) have emphasized the circular bioeconomy as the intersection of bioeconomy and circular economy activities

FIGURE 10. THE CIRCULAR ECONOMY AS THE INTERSECTION OF BIOECONOMY AND CIRCULAR ACTIVITIES



Adapted from Carus and Dammer, 2018

The case studies here feature many aspects of this intersection:

- Bio-based products
- Share, reuse, remanufacture, recycling
- Cascading use
- Utilization of organic waste streams
- Resource-efficient value chains
- Organic recycling, nutrient cycling

A key theme amongst nearly all case studies is water. In the arid environment of Southern Arizona, it is no surprise that most of the case studies below are in some way tied to water. Several case studies focus on innovative techniques, new technologies, or novel approaches to reduce both land and water requirements for agricultural production, many of which take place in controlled environment agricultural (CEA) systems (Case Studies 6.3, 6.4, 6.5, 6.6, and 6.7). In fact, many of the case studies employ vertical farming techniques with applications in different settings such as urban and peri-urban environments (Case Study 6.3) and underground (Case Study 6.6). Another case study explores the potential for shifting toward low-water-use, drought-tolerant crops that can be used to produce biobased industrial products (Case Study 6.1). Yet another case study (Case Study 6.2) illustrates how local organic material waste can be converted into useful properties to improve soil water and nutrient retention, increase yields, and potentially reduce land and water requirements to sustain crop production.

In many of the case studies, circularity is introduced into the bioeconomy through the use of waste and/or byproducts for productive uses. In Case Study 6.1, the residues generated through rubber production from guayule can be converted into value-added products such as biofuel and materials for making adhesives. In Case Study 6.5, the waste from aquaponics systems (otherwise known as sludge) could potentially make an effective, organic soil amendment, reducing fertilizer and water requirements for crops. In Case Study 6.2, biochar is produced using organic material waste, which is diverted away from landfills.

Another key theme is harnessing biological processes and utilizing technological advancements and specialized equipment to produce useful bioproducts, some of which are created through waste streams (Case Study 6.5, 6.8, 6.9). Case Study 6.8 highlights advancements that have been made to facilitate scaled-up cultivation of microalgae, which can generate high-value bioproducts such as proteins for human consumption, animal feed, nutraceuticals (e.g., omega-3 fatty acids), lipids for biofuels, cosmetic ingredients, and vitamins, among others. Case Study 6.9 illustrates how biological processes can be used to treat wastewater more effectively by removing contaminants of emerging concern. Not only does harnessing the power of plant processes do a more effective job, but it also addresses the concern of waste associated with treated wastewater. The processes proposed here results in valuable plant byproducts that can be used to make fibers, concrete, and myriad other industrial products.

While some of the case studies presented in the section below rely on technological advancements and patented and patent-pending applications, others achieve more efficient resource use by doing things in new and novel ways. For example, Case Study 6.4 illustrates that electrical energy demand for cooling and dehumidification can be reduced in a CEA system by integrating the production of mushrooms into a leafy greens CEA system. This is due to the high C02 emissions from the mushrooms, and the CO2 requirements of leafy greens.

Finally, at the pinnacle of circularity, Case Studies 6.6 and 6.7 explore food production in one of the most resource scarce environments- in space. Missions to the moon and other planets require sustainable life support systems, including Bioregenerative Life Support Systems (BLSS) that encompass food production by way of engineered controlled environments. In these fully closed systems, 100% of irrigation water and plant nutrients are recycled. The crops produced serve as food for astronauts, and crop production itself can play key roles in air regeneration and water purification and reuse. Case Study 6.7 illustrates a BLSS through a prototype lunar green house (LGH) while Case Study 6.6 uses underground vertical farming technology.

6.1. Reviving Guayule in Southern Arizona: A Circular Bioeconomy & Water Saving Crop

By Haiquan Li, Kamel Didan, Peter Waller, Dennis Ray, Diaa Eldin Elshikha

Private industry and universities partner to develop bio-based products for desert environments

Guayule (*Parthenium argentatum*) is a perennial, low-water-use, drought-tolerant, heat-resistant, woody shrub that grows natively in the desert of southern Texas and Mexico. It is now considered for producing commercial-grade rubber tiles and latex, resin adhesives, and biofuels, among other applications. There is an increasing demand for natural rubber. For instance, US imports of natural rubber increased by 13% in the first half of 2022, making guayule-based rubber production an economically appealing alternative industry.

The United States Department of Agriculture (USDA) funded a National Institute of Food and Agriculture (NIFA) research partnership between the University of Arizona, Bridgestone Tire Company (American, Inc), Colorado State University, the USDA, and New Mexico State University. This research program entitled 'The Sustainable Bioeconomy for Arid Regions Center of Excellence' (SBAR; https://sbar.arizona.edu/) from 2017 to 2023 aimed amongst other things to study the value of guayule to the region's economy with a focus on sustainability, water use under the looming climate change.

The SBAR project explored and tested systematic approaches to developing a guayule bioeconomy pipeline for the region that includes technologies of guayule planting, management, irrigation optimization of growth and yield of natural rubber biomass (Elshikha et al., 2021 & 2022), genetic improvement (Abdel-Haleem et al., 2019) and genomic characterization (Nelson et al., 2019), rubber extraction and processing (Luo et al., 2019), co-product identification (Cheng et al., 2020), logistics optimization (Vazquez et al., 2021), economic analysis (Moreno et al., 2022), precision management with drones and remote sensing (Combs et al., 2022), and environmental and cultural studies (Mealing et al., 2021). The project considered a series of optimization and study results and developed an economic Break-Even for New Crop Options Model (BENCO) (Omotayo 2022) to help growers estimate the economic risk and benefit of adopting guayule based on water and machinery availability and usability (Vazquez et al., 2021). The SBAR project industrial partner Bridgestone contributed through germplasm development, seed increase, development of cultivation technologies, including planting and harvesting equipment, and development of a rubber processing pipeline toward commercialization of guayule-based rubber and by-product production.

Although rubber production is the main profit stream, recycling and reusing the processing residue can add value to the industry and improve economic efficiency, which promotes the circularity of this bioeconomy. Two types of residues result from rubber extraction and processing. The first biproduct is the woody bagasse, which can be converted into biofuels for heating (Sproul et al., 2020), and generate nutrients and organic matter for soils. The other co-product is guayule resin (Luo et al., 2019), which can be used to make adhesives and other value-added metabolites, fatty acids, steroids, triterpenoids, and sesquiterpene esters (Cheng et al., 2020). Of note, triterpenoids are promising anticancer agents (Xu et al., 2021), among other applications.

Guayule can also serve as an effective cover crop in situations of severe water scarcity and possibly in solar farms and can reduce greenhouse gas emission when its byproduct is used as biofuels (Bayat et al., 2021, Moreno et al., 2022). Other benefits also include soil conservation as guayule has deep (1 to 2 meter), coarse taproots to collect water (Rousset et al., 2021).

Water conservation remains one of the most notable potential environmental benefits for our region, as guayule is a low water-use and drought tolerant crop (Sproul et al., 2020), potentially replacing other crops in areas where available water is limiting. Dennis Ray, a scientist with the SBAR project investigated a six week irrigation scenario, and found that it stimulates extra rubber production in comparison to other irrigation scenarios, while saving water. Growers are able to farm guayule on 2.4 ft (0.7 m) water per year, well within the normal allocation of water in Central Arizona now that Colorado River water delivery has been reduced. The SBAR team has developed an irrigation scheduling application named WINDS (Water-use, Irrigation, Nitrogen, Drainage, and Salinity) (Waller and Yitayew, 2015), that has since been calibrated with five years of guayule irrigation data to be used for irrigation scheduling of Guayule. Bridgestone plans to invest $40 million in the first phase of a processing plant (in Phoenix), with an additional $200 million investment later and has been recruiting farmers in Central Arizona to grow guayule.

This emerging bioproduct is fostering higher education by supporting graduate students in the Sustainable Bioeconomy and Bioenergy Emphasis within the Applied Biosciences GIDP program at the University of Arizona. It provided for training elementary, middle school and high school science teachers, created educational materials for classroom in different levels, and helps with preparing workforce for this industry.

For more Info:

- https://www.bridgestoneamericas.com/en/press-release-details.en.2022.bridgestone-announces-investment-in-guayule
- https://sbar.arizona.edu/

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6.2. Biochar for Irrigated Desert Croplands

By Shelby Höglund and Joseph Blankinship

Increasing soil water retention and nutrient availability to improve grain yield in southern Arizona using pyrolyzed forestry waste.

Biochar is a stable, carbon-rich product produced from organic materials (Lehmann, 2007). Mixing biochar into soil has been shown to improve soil water-holding capacity and nutrient retention when combined with an additional nutrient source (Artiola et al., 2012; Omondi et al., 2016). Biochar itself can retain water and nutrients due to its many pores, large surface area, and surface reactivity (Liang et al., 2006; Omondi et al., 2016). Because the type of organic waste (e.g., softwood) and method of production can vary, different types of biochars have different characteristics. Biochar contains carbon that persists for hundreds to thousands of years (Keiluweit et al., 2010), so adding biochar to soil increases long-lasting soil carbon content. In addition, mixing biochar with compost or adding biochar during the composting process (referred to as co-composting) can improve the nutrient content of finished compost (Hagemann et al., 2017).

Increasing biochar application rate does not always lead to proportional increases in soil water and nutrient retention. A greenhouse study at the University of Arizona Controlled Environment Agriculture Center found that increasing biochar application rate did not proportionally increase the capacity of a desert cropland soil to retain water or nutrients for plants. This study was conducted using a commercially available biochar produced from softwood in a modified biomass reactor at 760 °C. The soil's capacity to retain water for plants did not increase in treatments with biochar application rates lower than 73 Mg ha^{-1} (81 U.S. t ha^{-1}). Lower application rates also lost *more* plant-available phosphate via leaching whereas higher application rates retained more plant-available phosphate compared to the control treatment without biochar.

Agricultural applications for biochar. In other regions of the world, biochar is used in soil to improve crop yield and certain soil qualities. Applying biochar to croplands can provide several environmental benefits, but not without limits. Site-specific research should guide decision-making. Because biochar improves soil water retention, its use in croplands in the Southwestern U.S. may help sustain food production as water resources become scarcer. This was investigated in a field study at the University of Arizona Campus Agricultural Center that compared three soil amendments: 1) biochar mixed with finished compost, 2) co-composted biochar, and 3) a control treatment with compost. Three irrigation treatments were implemented to investigate if biochar could maintain or increase crop yield when irrigation frequency was reduced.

When soils were frequently irrigated in this study, biochar and co-composted biochar produced 31% and 45% greater grain yield in the first year compared to the control treatment. However, biochar treatments did not improve grain yield compared to the control when irrigation frequency was reduced. In addition, biochar treatments only affected plant-available nutrients in the first year of this study; soils with co-composted biochar had greater available nitrate while soils with biochar and co-composted biochar reduced available phosphate compared to the control. Based on these results, biochar can increase grain yield, but may not alleviate irrigation water requirements. Because biochar increased crop yield per area, biochar can potentially reduce land area required for growing crops while maintaining total yield and therefore less land will need irrigation.

Furthermore, compost manufacturers can use biochar to improve the quality of finished compost. In the field study, co-composting biochar increased the concentration of nitrate and phosphate in finished compost. As mentioned, more nutrients in the finished compost did not result in greater nutrient availability when amendments were mixed with soil. Composting with biochar also accelerated the composting process. A shorter composting process will reduce equipment and labor requirements as well as move materials through compost facilities faster.

Biochar for Circularity. Producing biochar and co-composted biochar from local organic material for use as soil amendments is a way to reuse material and recycle nutrients (from compost) and carbon back into soil. Organic materials often used to produce biochar include wood (chipped wood, landscaping waste, forestry residue, etc.) and agricultural waste (straw, crop residue, etc.). Producing biochar and co-composted biochar diverts organic materials from landfills and has the potential to reduce the demand for chemical fertilizers.

For more information:

U.S. Biochar Initiative | https://biochar-us.org

International Biochar Initiative | https://biochar-international.org/

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6.3. Urban and Peri-Urban Vertical Farming

By Joel L. Cuello

Current research and engineering innovations for a potential vertical-farming industry in southern Arizona to be linked with external bioeconomy nodes to achieve circularity.

To meet the food demand of a global population that will increase from today's approximately 8 billion to about 9.7 billion, the United Nations projects that food production will need to increase by 70%, necessitating a doubling in crop production from 10 billion tons to 20 billion tons by 2050 (FAO, 2009; Ray and Schaffer, 2011). Given that agriculture already makes use of about half of all habitable land on the planet, consumes over 70% of all current freshwater withdrawals worldwide, and expends 30% of the global energy demand to food production and its supply chain, it is clear that a doubling of crop production will put enormous pressures on land, water and energy resources worldwide, particularly in arid and semiarid regions of the world (Cuello, 2018).

People are drawn to live in cities because cities constitute the world's undisputed economic engine. Just 600 cities today account for about 60% of the global economic output (Dobbs et al., 2011). By 2025, the world's top **600** cities will be home to an estimated 220 million more people of working age and will account for more than 30% of the expansion of the potential global workforce (Dobbs et al., 2011).

An affirmative stance for urban agriculture is in part supported by the argument that cities, with their infrastructures and centralized planning for supplying water and energy as well as for treating and reusing wastewater and even generating renewable energy, lend themselves well to organized and potentially more efficient utilization of water and energy for crop production.

(a) Vertical-Hive (V-HIVE) Green Box

(b) The BORING Vertical Farm

(c) I-AMEND Nutrient Delivery System

(d) Mobile and Modular Vertical Farming Systems

Figure 1. The University of Arizona Biosystems Engineering Laboratory portfolio of patented/patent-pending originally designed scalable and automated vertical-farming growing systems and nutrient-delivery systems for scaled-up vertical farming of vegetables, fruit berries, herbs and microgreens, among others.

Urban agriculture takes on several forms including establishing community gardens on vacant lots and, more recently, rooftop greenhouses. Vertical farming constitutes another form of urban agriculture in which the crops are produced in vertically stacked growing shelves or trays in an enclosed environment (Cuello, 2014). There are two paradigms of vertical farms: (1) the warehouse vertical farm; and (2) the modular vertical farm. Warehouse vertical farms, also referred to as plant factories as pioneered in Japan, typically employ hydroponics technology, or soil-less agriculture, through which crops are grown in liquid nutrient solutions. The crops are also provided either exclusive or supplemental electric lighting typically using light-emitting diodes (LEDs). Japanese-designed vertical farms have always focused on developing controlled-environment hydroponic technologies that enable intensive crop production with significantly increased yield (2x or 3x), at significantly reduced water input (about 80% to 90% less), and with reduced land footprint without the need for arable land as compared with open-field farming.

The University of Arizona Biosystems Engineering Laboratory in the Department of Biosystems Engineering has been building a growing portfolio of patented/patent-pending originally designed scalable and automated vertical-farming growing systems and nutrient-delivery systems (**Figure 1**) for the scaled-up vertical farming of vegetables, fruit berries, herbs and microgreens, among others.

Table 1. Urban/Peri-urban vertical farming for scaled-up production of vegetables, fruit berries, herbs and microgreens, among others

Case Innovations	Case Products	Case Byproducts for Circular Economy Design	Byproducts from External Industry Nodes as Case Inputs for Circular Bioeconomy Design
Vertical-Hive (V-HIVE) Green Box (Cuello et al., 2023) The BORING Vertical Farm (Cuello et al., 2022) I-AMEND Nutrient Delivery System (Cuello et al., 2022) Mobile and Modular Cultivation Systems for Vertical Farming (Cuello et al., 2021)	Food Crops Captured Carbon for Credit	Nutrient wastewater Inedible biomass as source of nutrients	Point-source carbon dioxide generated by electric power plants, etc. Inedible biomass from greenhouses as source of nutrients Aquaculture wastewater as source of nutrients Food & beverage manufacturing effluent as source of nutrients and water

Southern Arizona represents a competitive location for the establishment of an urban/peri-urban vertical-farming industry owing to the availability and relatively low cost of land as well as its year-round abundance of solar radiation, among others. **Table 1** shows how an urban/peri-urban vertical-farming industry in southern Arizona could be linked with external bioeconomy nodes to achieve circularity. Potential input feed could come from external industry nodes, including electric power plants, greenhouses, open-field agriculture, aquaculture operations, and food and beverage manufacturing facilities, among others.

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6.4 Leafy greens and mushroom production integrated CEA system

By Murat Kacira and Barry Pryor

Leafy greens and mushroom production in integrated controlled environment agriculture (CEA) system for circularity

Projections forecast that the global demand for food, energy, and freshwater will increase considerably over the next decades due to multiple factors, e.g., increases in population growth and mobility, economic development, urbanization, diversified diets, cultural and technological changes, and climate change (FAO, 2014). There is growing demand for local year-round production of safe, healthy, nutritious, and affordable fruits, vegetables, and protein sources. One of the reasons for this rising local demand relates to consumer perception that long distance transport of food from field production sites significantly deteriorates freshness, product quality and nutritional content upon arrival at distant markets. Another important aspect of the local-grown movement is the desire to move toward environmental sustainability with reduced carbon footprint.

When hydroponic cropping systems are stacked in vertical tiers within repurposed warehouses, with overhead LED lighting at each production level, this type of indoor agriculture is termed vertical or indoor farming (Figure 1). Compared with field production of the same crops per land-area-footprint and annual production basis, the indoor farming systems can be at least two orders of magnitude more productive compared to open-field agriculture (Kozai, 2013). The emerging indoor farming industry has attracted venture capital investors and entrepreneurs, and is rapidly growing with technological developments, but often without deep knowledge of crop needs, engineered and integrated system designs, and lack of resource conserving and innovative environmental control strategies. A major challenge to address for indoor vertical farming-based systems is to reduce use of electrical energy demanded by the LED lighting systems which accounts for about 40% of total energy use. This can be achieved in several ways, including innovative light-delivery designs for LED fixtures, engineered air conditioning system design and resource conserving environmental control strategies, optimized growth prescriptions including interactions between light intensity and CO_2 levels for crops during each crop growth stage, and an integrated systems-based approach to co-produce and reuse/re-cycling of resources for smart, sustainable, and profitable indoor agriculture.

Consumption and demand for mushrooms as a protein or a health benefiting compounds source has been significantly increasing in Arizona and across the US, and US production has increased nearly 30% over the last 10 years (2018, NASS). Currently, most of the statewide demand for mushrooms is met by larger producers out of state, notably Pennsylvania. However, mushrooms are perhaps the most perishable product in the produce aisle and regional production provides a much higher quality product over that transported for many miles and many days. This difference in quality is immediately recognizable, particularly with specialty mushrooms. Thus, regional markets support developing local mushroom industries, particularly in the specialty mushroom category. Indeed, specialty mushroom production is increasing in many states to supply local markets, and this presents strong opportunity for new business development.

Because mushrooms are produced in indoor controlled environment facilities, new mushroom producers can enter the market at many economic levels, as either small or large business entities. Another important aspect of mushroom production is that significant amounts of CO_2 are emitted into the production system which must be vented out (e.g. wasted) to enable and optimize mushroom production. However, this valuable wasted CO_2 is in great demand and can be re-cycled as a resource for crops, such as leafy greens, in indoor CEA production systems. It can even be possible to reduce the light intensity, minimizing the demand for electrical energy, while slightly increasing the CO_2 levels to achieve the desired crop yield and qualities. The cost of increased CO2 levels to enhance the crop yield is much more cost effective than increased light intensity for enhanced crop yields, thus lowered light intensity with slightly increased CO_2 level can lead to significant energy savings and enhance profitability of the production. Some of the indoor crop growers also use natural gas burners in indoor growing spaces to generate CO_2 for the crops which leads to increased heat and water in the growing space further demanding for energy use for cooling and dehumidification, which accounts about 50% of the total electrical energy use in indoor agriculture systems. Therefore, the use of CO_2 ejected from mushroom production system can reduce the electrical energy demand for cooling and dehumidification and lead to enhancing environmental sustainability using a re-cycled resource. However, to our knowledge such integrated system with hydroponics based leafy greens and mushroom production in indoor vertical farming system has not been experimentally evaluated and implemented to date at scale. With experimental and modeling-based research conducted at UArizona-CEAC, Shasteen (2022) demonstrated 15% electrical energy savings can be achieved with 11.2 daily light integral (DLI) and 1000 ppm CO_2 setpoints compared to 13. 5 DLI with 500 ppm CO2, with both control setpoints resulting in same fresh lettuce crop yield of 200 gr per head. Furthermore, Chung (2020) found that it is possible to grow four head lettuce per one mesquite/alfalfa substrate bag with Pleurotus ostreatus mushroom grown, or fourteen head lettuce per one mesquite/alfalfa substrate bag with Ganoderma lucidum mushroom grown (Figure 2).

Figure 1. Vertical Farming Research and Education Facility (UAg Farm) at UArizona-CEAC.

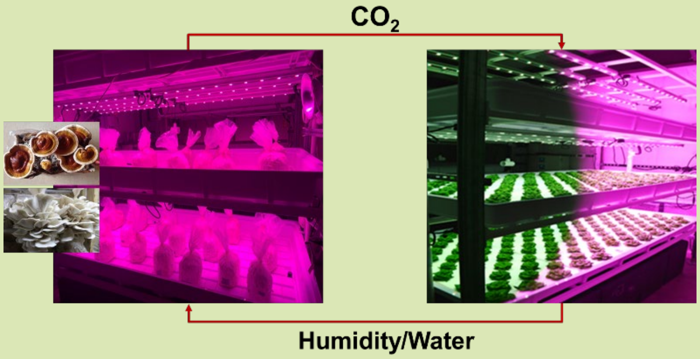

Figure 2. Leafy green & mushroom integrated CEA production system

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6.5 The Circular Bioeconomy of Decoupled Aquaponics

By Matt “Rex” Recsetar and Kitt Farrell-Poe

Using aquaponics and its byproducts at the University of to save water and improve plant production in hydroponics and soil.

Aquaponics is a food production method that utilizes the nutrients from fish waste to grow plants in a soilless medium. While it has been around for many years, in one form or another, only recently has it become more viable on a larger scale utilizing controlled environment agriculture techniques. Aside from using the waste stream from fish culture to grow plants, it saves on the use of hydroponic nutrients, many of which are derived from industrial processes such as mining and extraction. In other words, the carbon offset from using fish feed as the source of nutrients is significant. Recent studies by the Recsetar Lab examined cost savings in aquaponics and showed that aquaponics production not only saves water over traditional soil culture, but over hydroponics as well (Recsetar, unpublished data). In addition, when scaled to commercial production levels, aquaponic-grown plants in that study cost 85% less to grow than hydroponic-grown plants, based on current costs of the nutrient salts used in the hydroponic formulation, not considering capital costs.

In most commercial aquaponics systems, a recirculating aquaculture system (RAS) is typically run as a standalone system, which is decoupled from the hydroponic component; often referred to collectively as decoupled aquaponics. Solid wastes (comprised of fish poop and uneaten fish feed) are removed from the RAS through various filtration processes, while the filtered effluent from the RAS is used to feed the hydroponic component as needed; it does not return to the fish system, contrary to coupled aquaponics, in which it does. This allows for each system to be managed separately to optimize conditions for both fish and plants and thus maximize production of both.

The solids collected and removed through sedimentation or mechanical filtration in the RAS can be digested either aerobically or anaerobically to mobilize additional nutrients and reduce waste production (Monsees et. al., 2017). These solids would otherwise end up in landfills or emptied into the environment with or without prior treatment to meet EPA effluent guidelines for Concentrated Aquatic Animal Production (EPA, 2004). In general, aquaponics is thought of as a sustainable growing method, but externalities such as solid waste (sludge) production are often overlooked in larger systems. The Recsetar Lab demonstrated that this “sludge” can be aerobically mineralized to significantly increase the nutrient content of the effluent, but they observed in multiple systems that not all the solids were decomposed during this aerobic process. In a recent 2022 study in the Recsetar Lab, the residual solid sludge from three aquaponics systems including a commercial aquaponics farm in Tucson was collected and dewatered to create a stabilized biosolid. After lab analysis, it was found that these aquaculture biosolids contain adequate nutrient content to make an effective, organic soil amendment, exhibiting an N-P-K of 3.8-2.6-1.3 compared to Arizona wastewater biosolids which are estimated to have an N-P-K of 3.6-3.3-0.4 (Artiola, 2011), which demonstrates a valuable waste revenue stream, thus eliminating the final waste stream in aquaponics food systems.

To show the effectiveness of this circular bioeconomy, my aquaponics interns and I applied for and received a Campus Sustainability Fund Grant in fall of 2022 to develop a sustainable fruit orchard utilizing aquaponics sludge, stabilized aquaponics biosolids, and rainwater harvesting from the greenhouse roof to demonstrate this completely sustainable endeavor. Fruit grown in this sustainable orchard will be harvested by students and given to the Campus Pantry here at the University of Arizona. Through the project we will measure and show the water and fertilizer savings for producing equivalent quantities of various fruits. Results are forecasted by 2024 for plums, peaches, lemons, and oranges.

Although hydroponically grown plants may be the main profit stream in aquaponics, followed by sale of fish, additional value can be attained through sale of aquaponics effluent and aquaponics stabilized biosolids, thus improving efficiency and promoting the circular bioeconomy. Aquaponics can be utilized all over the world, to grow fish and plants together while also generating biproducts for improving soil-based agriculture and tremendous water savings. In a recent experiment, the Recsetar Lab showed that aquaponically grown plants utilized 40% less water than hydroponically grown plants to achieve the same yield (Recsetar et. al., unpublished data). Consensus says that hydroponics can achieve up to 90% water savings over soil-based agriculture (Bradley and Marulanda, 2001; Sharma et. al., 2018). While wastewater biosolids have been shown to increase soil moisture retention and improve soil aeration and organic content (Tsadilas, 2005; Artiola, 2011; Qin et. al. 2012), no studies have been done to show the effectiveness of aquaculture biosolids in soils. The possibilities for promoting resource reuse in aquaponics has created several opportunities for graduate student research projects, including nutrient modeling, microbiome manipulation and even utilization of AI to manage water and nutrients for specific crops; all of which will have a positive impact on our world.

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6.6 Underground Vertical Farming in Southern Arizona as Inspired by Underground Vertical Farming on the Moon and Mars

By Joel L. Cuello

Current research and engineering innovations for underground vertical farming in southern Arizona to be linked with external bioeconomy nodes to achieve circularity.

Southern Arizona represents a competitive location for the establishment of an urban/peri-urban vertical-farming industry (Cuello, 2014; Cuello, 2018) in view of the availability and relatively low cost of land as well as the year-round abundance of solar radiation, among others. A significant disadvantage, however, is its appreciable temperature swings between seasons in a given year.

The hot season in Tucson lasts on average for 3.7 months, from *May 25* to *September 17,* with an average daily high temperature exceeding 34℃ (*94°F).* July is the hottest month of the year in Tucson, with an average high of 38℃ (*100°F)* and low of 25℃ *(77°F)*. The *cool season, contrastively,* lasts for *3.2 months*, from *November 22* to *February 28*, with an average daily high temperature below 22℃ (*72°F)*. December is the coldest month of the year in Tucson, with an average low of 6℃ *(43°F)* and high of 19℃ (*66°F)* (weatherspark, 2023).

Incidentally, southern Arizona is home to underground silos that were built for the Cold War's Titan II missile program, which began in 1963 and was decommissioned in the 1980s. The U.S. once operated more than 50 Titan II missile sites across the country, and 18 of them are located in southern Arizona (**Figure 1**). Most of these underground silos have been purchased by private buyers. In 2019, an underground Titan missile silo site east of Picacho Peak was sold, and in 2020 a former missile complex in Oracle, northeast of Tucson, and of a silo in Benson, southeast of Tucson, were listed for sale (Reagor, 2020). Potential buyers cited various reasons for acquiring the silos, which included converting them into a medical marijuana production facility (Reagor, 2020). A significant advantage of these southern Arizona underground silos, or of underground facilities in general, is their natural capacity to maintain lower and very stable ambient temperature year-round compared with facilities located on the surface.

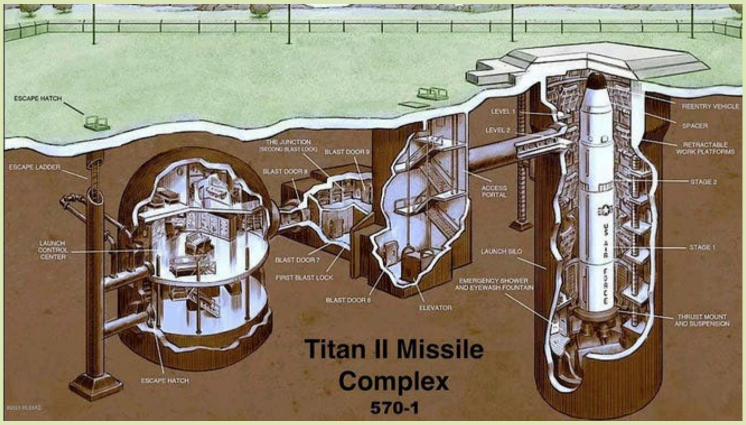


Figure 1. Titan II missile complex in southern Arizona showing underground silos (Reagor, 2020).

The concept of an underground vertical farm has already been commercially realized, with the first case attributed to that for Zero Carbon Farms in London, U.K. that makes use of a former government-built World War II underground shelter located at 33 meters deep under southwest London (Broom, 2021). The vertical farming company owns a hectare of underground growing space producing greens, including Thai basil, garlic chives and pea shoots (Broom, 2021).The University of Arizona Biosystems Engineering Laboratory in the Department of Biosystems Engineering had designed and operated a NASA-sponsored Subterranean Plant Growth Facility (SPGF) (Cuello et al., 2000; Cuello et al., 2001) that used above-ground solar concentrators which collected and concentrated solar irradiance for conveyance through fiberoptic cables to provide solar lighting -- in hybrid combination with electric lighting, such as LEDs -- to crops grown in underground controlled-environment growth chambers (**Figure 2**).

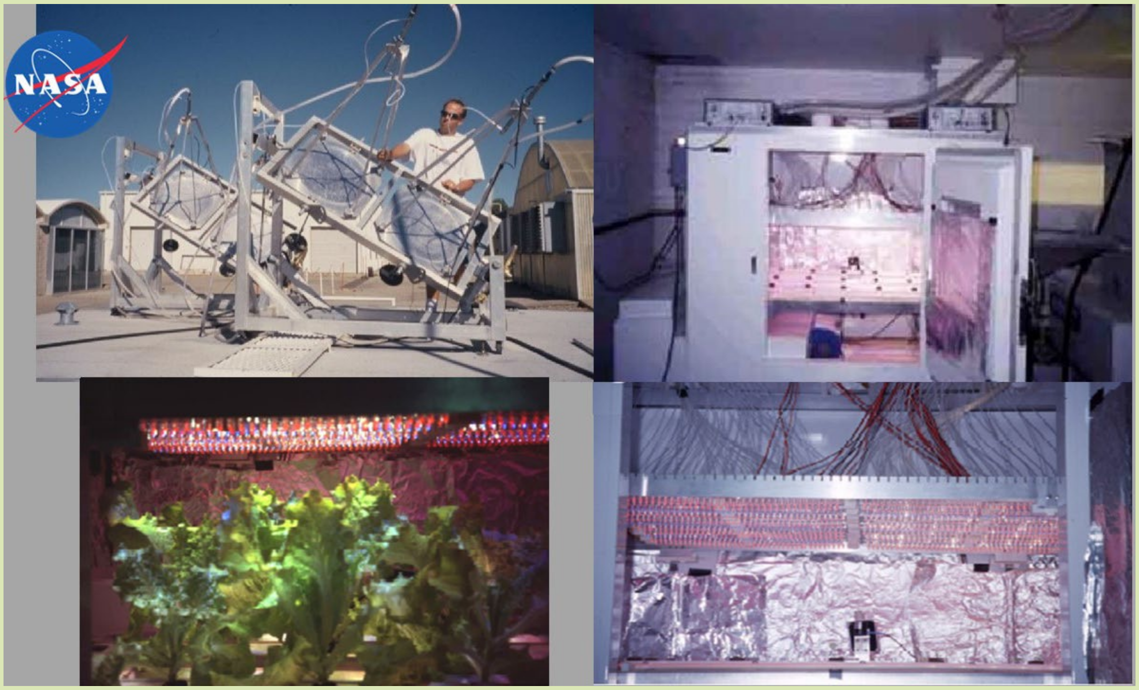


Figure 2. The University of Arizona NASA-sponsored Subterranean Plant Growth Facility (SPGF) equipped with above-ground solar concentrators for collection and conveyance of solar irradiance through fiberoptic cables to provide solar lighting -- in hybrid combination with electric lighting, such as LEDs -- to crops grown in underground controlled-environment growth chambers.

Meanwhile, with reinvigorated commitment to space exploration that includes long-duration crewed missions on the Moon, Mars and beyond, a handful of national space programs such as NASA in close cooperation with private aerospace companies – including SpaceX, Blue Origin, Virgin Galactic, NanoRacks, Voyager Space, Lockheed Martin, Sierra Space and Bigelow Aerospace, among others -- are currently developing the necessary innovations in the service of such missions, including innovations for food production in the extraterrestrial environment.

Long-duration crewed missions on the Moon, Mars and beyond require sustainable and resilient life support systems, including bioregenerative life support systems that encompass food crop production by way of engineered controlled environment. The crops serve as food for astronauts, and crop production itself can play key roles in air regeneration and water purification and reuse within an extraterrestrial human habitat.

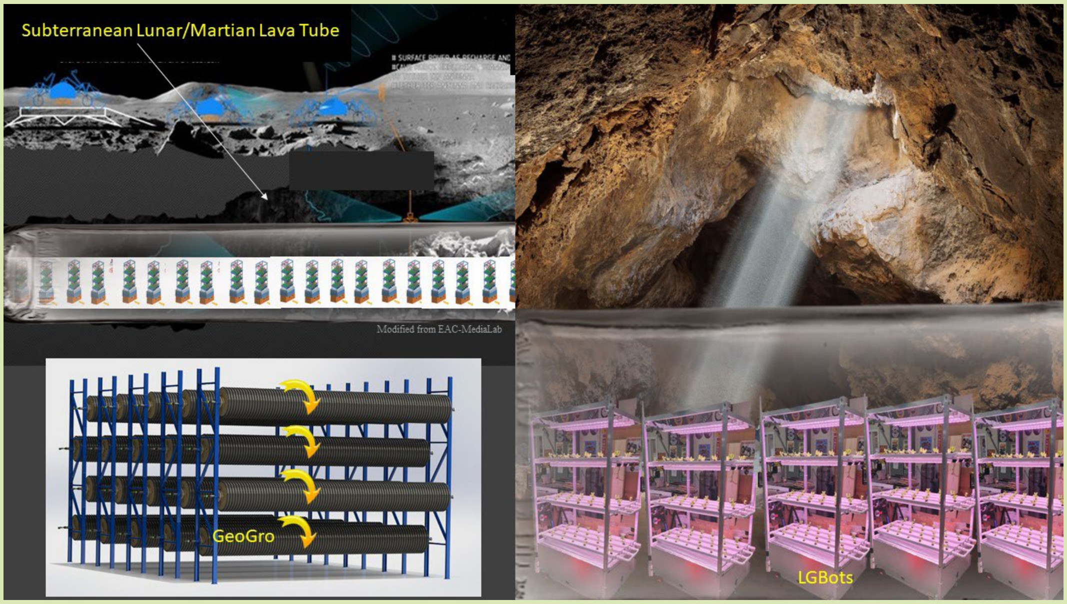
A significant limitation in growing crops in an extraterrestrial environment is its extreme environment that is simply fatal to biological organisms. In addition to the lack of available flowing water and arable land, the surfaces of the Moon and Mars are constantly exposed to ionizing radiation, bombarded by meteors and micrometeorites, often plagued by gigantic dust storms, and regularly treated to wild diurnal swings in ambient temperature. Thus, the processes of erecting, building, operating and maintaining structures on the surfaces of the Moon and Mars are replete with challenges, not the least of which is the requirement for special materials that possess both significant mechanical strength and durability and the ability to withstand sustained exposures to extreme radiation, repetitive and large thermal fluctuations, and frequent pounding by micrometeorites and dust storms.

To this end, the Biosystems Engineering Laboratory – in partnership with external experts, i.e., structural and systems engineer Matteo Pietrobelli and vertical farming entrepreneur Mackenze McAleer – has designed the patent-pending BORING (BurrOwing & Regenerative IN-Ground) Vertical Farm. The BORING Vertical Farm is characterized by its embedded location in subterranean spaces, such as lava tubes, beneath the surface of the Moon and Mars, and was conceived and designed to enable the productive growth of crops in space for long-duration and permanent human habitation (Cuello et al. 2022) (**Figure 3**).

A preferred embodiment of the BORING Vertical Farm is one comprising an inflatable chamber or group of chambers using materials such as rigidized gossamer structures, thermally cured thermoset composites, metamaterials, annular foam-rigidized structures or aluminum and film laminates.

The crop growing systems to be used in a BORING Vertical Farm may be any of or modifications of existing growing systems that have, for instance, been developed and demonstrated for the International Space Station. Two preferred novel embodiments include the mobile and modular LifeGrow Bots (LG Bots), a patent-pending innovation by the Biosystems Engineering Laboratory, and the soil-based GeoGro, a patented innovation by M. McAleer (**Figure 3**).

The BORING Vertical Farm, in whole or in part, serves to directly inform design embodiments of underground vertical farms for southern Arizona.



Modified from EAC-MediaLab

Figure 3. Depiction of embodiments of the patent-pending BORING (BurrOwing & Regenerative IN-Ground) Vertical Farm, characterized by its embedded location in subterranean spaces, such as lava tubes, beneath the Lunar or Martian surface and designed to enable productive growth of crops in space for long-duration human habitation. Examples of its crop growing systems include the mobile and modular LifeGrow Bots (LG Bots), a patent-pending innovation by the Biosystems Engineering Laboratory, and the soil-based GeoGro, a patented innovation by M. McAleer.

Underground vertical farms in southern Arizona could be linked with external bioeconomy nodes to achieve circularity (Table 1). Potential input feed could come from external industry nodes, including electric power plants, greenhouses, open-field agriculture, aquaculture operations, and food and beverage manufacturing facilities, among others.

Table 1. Underground vertical farms in southern Arizona for scaled-up production of vegetables, fruit berries, herbs and microgreens, among others

Case Innovations	Case Products	Case Byproducts for Circular Economy Design	Byproducts from External Industry Nodes as Case Inputs for Circular Bioeconomy Design
The BORING Vertical Farm (Cuello et al., 2022) I-AMEND Nutrient Delivery System (Cuello et al., 2022) Mobile and Modular Cultivation Systems for Vertical Farming (Cuello et al., 2021)	Food Crops Captured Carbon for Credit	Nutrient wastewater Inedible biomass as source of nutrients	Point-source carbon dioxide generated by electric power plants, etc. Inedible biomass from greenhouses as source of nutrients Aquaculture wastewater as source of nutrients Food & beverage manufacturing effluent as source of nutrients & water

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6.7 Bioregenerative Life Support for Space Habitats and Earth Applications of Controlled Environment Agriculture

By Gene Giacomelli and Murat Kacira

Increasing the capability and robustness of water and atmospheric revitalization within a closed system by food plant production practices.

Bioregenerative Life Support Systems (BLSS) can be achieved with food production procedures within enclosed environmentally controlled confines which recycle 100% of irrigation water and plant nutrients, while collecting inedible biomass for recycling. In the process CO_2 is transformed into plant biomass for human food while oxygen is created by photosynthesis.

BLSS represents an important solution to the problem of sustaining long-term human presence in space and on other planets. A BLSS employs plants and crop production to provide air revitalization, water recycling, waste recycling, and food production. BLSS developments have been sponsored by many space agencies around the world including NASA, ESA , China and JAXA (e.g. MELISSA program for ESA[1] and CELSS for NASA[2].

The University of Arizona team of engineers, scientists, and industry partners has been actively proposing novel design and implementation of BLSS for future habitat and science outposts[3]. The conceptual lunar habitat is equipped with a BLSS within a lunar greenhouse prototype (LGH), and would be covered with regolith (Figure 1). The project involves the design, construction, and operation of an innovative 5.5 m long by 1.8 m diameter membrane-covered LGH with a hydroponic crop production system in a controlled environment that exhibits a high degree of future lunar mission fidelity. The demonstration LGH module operates and is monitored with a Cable Culture hydroponic crop system[4] producing some of the NASA candidate crops. The research supported by the NASA Steckler Space Grant Phase I (January 2010 – June 2011), II (July 2011 – June 2013), and III (2014 – 2017)[5] focused on continuing the operation of the UArizona-BLSS LGH.

Figure 1. Prototype BLSS Lunar Greenhouse (LGH) with Cable Culture currently in operation at UA-CEAC[8]

The overall objective of this project was to establish the technical merit and feasibility of a high-fidelity membrane structure (i.e. the existing prototype Lunar Greenhouse (LGH)), and its food production system (Cable Culture) by demonstrating and evaluating its performance. NASA targeted crops have been grown, in combination, to maturity, including lettuce, tomato, sweet potato, and strawberry or cowpea, to maximize both the volume space utilization of the LGH and the radiation intercepted for plant growth, and to determine the biomass production per area (or volume) per unit time and to quantify water recycling, air revitalization, food production, energy usage and labor demand per unit of production.

The production outputs and resource inputs of the LGH system were determined in Phase I as the average daily increase of plant biomass (0.06 ± 0.01 kg m^{-2} day^{-1} wet weight basis (ww), and average water condensate production

(21.4 ± 1.9 L day^{-1}) while consuming an average of 25.7 L day^{-1} of water and 0.22 kg day^{-1} of CO_2 with an average electrical power consumption of 100.3 kWh day^{-1} (361.1 MJ day^{-1}). Thus, the LGH system produced about 24 ± 4 g biomass (ww) per kWh (83 g biomass (ww) per MJ) of electrical energy with a labor demand of an average of 35.9 min day^{-1} for operations[6,7].

Terrestrial agricultural applications for BLSS

Crop production in controlled environment agriculture (CEA) greenhouses can provide year-round production of high-quality food crops in many Arizona locations. For instance, CEA production of leafy greens can use 90% less water per unit produced and tomato production can use 15-20% less water per unit produced compared to seasonal open field agriculture, with consistent yields and assured quality. BLSS concepts that reduce inputs of energy, water, fertilizers, labor, and disposable wastes required for space agriculture can be similarly applied for Earth-based agriculture. Water delivery, plant water use and water disposed are optimized for the most efficient production, while crops 'pack out' at nearly 100% with little losses during production. There now exists the equivalent of thousands of acres of food crop production throughout the US in economically viable greenhouse businesses, yet they produce as little as 10% of the yearly national demand for vegetables such as lettuce, leafy greens, and tomatoes. Enhancing CEA in Arizona and other semi-arid regions, especially with limited natural water supplies, will be a timely alternative for food production agriculture.

BLSS for Circularity

Producing food crops within local greenhouse systems leads to recycling irrigation and nutrient water, eliminating environmental impact of water and soil contamination with fertilizer salts, and maximizing fresh quality vegetables to markets with minimized loss to shrinkage in the markets. Inedible biomass is concentrated within the greenhouse allowing for ease of collection and organized for composting providing organic matter for soil amendments, or processing to extract nutrients for future crops. Unused nutrient water can be applied to traditional outdoor crops. Solar energy availability for production of electrical power can become the source of input energy to the CEA food production system.

For more information:

Controlled Environment Agriculture Center, University of Arizona: Home | Controlled Environment Agriculture Center (arizona.edu)

Ohio Controlled Environment Agriculture Center: Home | Ohio Controlled Environment Agriculture Center (osu.edu)

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6.8 Microalgae for High-Value Bioproducts

By Joel L. Cuello

Current research and engineering innovations for a potential microalgal high-value products industry in southern Arizona to be linked with external bioeconomy nodes to achieve circularity.

Commercial large-scale production of microalgae began in the late 1960s in Japan, then spread throughout the globe in the 1970s and 1980s. In recent years the number of commercial large-scale facilities around the world has increased at a nearly exponential rate as demand for animal feed, nutraceuticals, vitamins and lipids, biofuels and bioplastics has increased.

The global production of microalgal biomass was estimated to be more than 5,000 dry tonnes in 2005 with a value of more than U.S. $1.25 billion, which excluded the value of processed products (Spolaore et al., 2006). Annually, about 3,000 dry tonnes of Spirulina are produced in China, India, Myanmar, the United States, and Japan; 2,000 dry tonnes of Chlorella in Taiwan, Germany, and Japan; and 1,200 dry tonnes of Dunaliella salina in Australia, Israel, the United States, and China (Spolaore et al., 2006). In 2008, the global production of microalgal biomass was estimated to have reached 9,000 dry tonnes per year (Benemann, 2008).

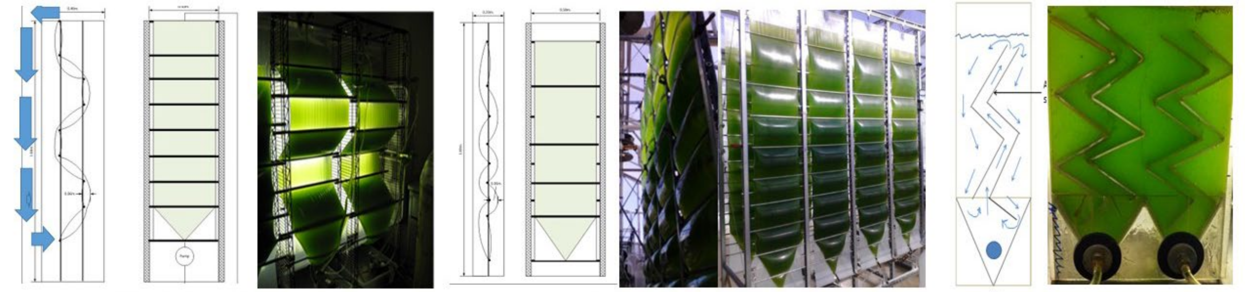
There are two general approaches in the mass cultivation of microalgae. Open systems (such as open ponds or raceways) are economical to build and operate; however, they have major disadvantages, including significantly high contamination risks, fluctuations in environmental conditions, and significantly lower and less reliable productivity. Closed systems (such as photobioreactors), though relatively costlier, have the advantages of control of environmental conditions, significantly lower risk of contamination, and higher productivity and reliability than open systems.

The photoautotrophic growth of microorganisms or cells is enabled by the photosynthetic capacity of the chlorophyll-containing microorganisms or cells, whereby carbon dioxide (CO_2), through photosynthetic carbon fixation, serves as the carbon (or food) source. Photoautotrophic growth requires the presence of light for photosynthesis to occur. A steady supply of CO_2 when light is available also promotes culture growth.

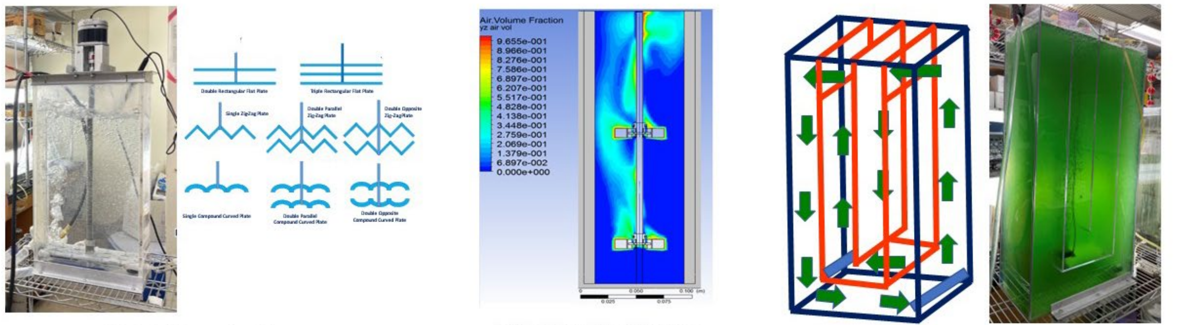
Heterotrophic growth, by contrast, takes place when the microorganisms or cells, in the absence of photosynthetic CO_2 fixation, rely on exogenous carbon-based molecules, typically sugars such as glucose or sucrose, present in the liquid culture medium as their carbon (or food) source. This mode of growth also requires a steady supply of oxygen (O_2) which the microorganisms or cells need as they breakdown the carbon-based molecules through the process of respiration. Since light is not essential, heterotrophic production is generally carried out in darkness. Mixotrophic growth takes place when the microorganisms or cells grow both photoautotrophically and heterotrophically.

The University of Arizona Biosystems Engineering Laboratory in the Department of Biosystems Engineering has been building a growing portfolio of patented/patent-pending originally designed scalable bioreactors with superior mixing or hydrodynamic characteristics, if not also with modular design and lower-cost, for the scaled-up cultivation of microalgae cultures as well as other microbial cells (**Figure 1**). The high-value products generated include proteins for human consumption, animal feed, nutraceuticals (e.g., omega-3 fatty acids), lipids for biofuels, cosmetic ingredients and vitamins, among others.

Southern Arizona represents a competitive location for the establishment of a microalgal high-value-products industry owing to the availability and relatively low cost of land as well as the year-round abundance of solar radiation, among others. **Table 1** shows how a microalgal high-value-products industry in southern Arizona could be linked with external bioeconomy nodes to achieve circularity. Potential input feed could come from external industry nodes, including electric power plants, municipal wastewater facilities, greenhouses, open-field agriculture, aquaculture operations, and food and beverage manufacturing facilities, among others



(a) Regular Accordion Bioreactor (b) Air Accordion Bioreactor (c) Accordion Air Loop Bioreactor



(d) Axial Dispersion Bioreactor (e) Air Stirred Tank Reactor (f) Compound Air Loop Reactor

Figure 1. The University of Arizona Biosystems Engineering Laboratory portfolio of patented/patent-pending originally designed scalable bioreactors with superior mixing or hydrodynamic characteristics, if not also with modular design and lower cost.

Table 1. Scaled-up cultivation in bioreactors of microalgae cultures for high-value products.

Case Innovations	Case Products	Case Byproducts for Circular Economy Design	Byproducts from External Industry Nodes as Case Inputs for Circular Bioeconomy Design
Regular Accordion Bioreactor (Cuello & Ley, 2014) Air Accordion Bioreactor (Cuello et al., 2020b) Accordion Air Loop Bioreactor (Cuello et al., 2020a) Axial Dispersion Bioreactor (Cuello et al, 2018) Air Stirred Tank Reactor (Cuello et al, 2020)	Food (e.g., protein, etc.) Animal Feed Nutraceuticals Cosmetic Ingredients Biofuel Feedstock (e.g., lipids) Fertilizer	Nutrient wastewater Inedible biomass as source of nutrients	Point-source carbon dioxide generated by electric power plants, etc. Inedible biomass from greenhouses as source of nutrients Cellulosic biomass (e.g., switch grass, hemp) as source of glucose for heterotrophic production Municipal wastewater as source of nutrients for non-food products

Compound Air Loop Reactor (Cuello & Mason, 2023)	Captured Carbon for Credit		Aquaculture wastewater as source of nutrients Food & beverage manufacturing effluent as source of nutrients & water

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6.9 Phyto-mediated Wastewater Treatment for Removing Contaminants from Wastewater Effluent

By Matt Recsetar and Joel Cuello

A case study for using a recirculating hydroponic bioreactor to remove contaminants of emerging concern from Arizona wastewater effluent.

At least 45 contaminants of emerging concern (CECs) have been detected in tertiary treated wastewater effluent in Tucson, Arizona. These contaminants, ranging from pharmaceutical compounds and personal care products (PPCPs) to disinfection byproducts, household chemicals and various endocrine disrupting compounds (EDCs), are not currently regulated by the EPA. Little is known about the long-term effects of these contaminants but studies have already shown negative effects on aquatic organisms (Ashton et al., 2004; Gomes et al., 2003; Kostich et al., 2014). Since these compounds are not always fully removed through the current wastewater treatment process, many of them ultimately end up in drinking-water aquifers as the effluent is recharged into the ground. While they may not be detectable in drinking water quite yet due to dilution effects and limits of detection of sensor or instrument used, it is only a matter of time before they start showing up.

With the circular bioeconomy in mind, Drs. Recsetar and Cuello of the Department of Biosystems Engineering designed a scalable strategy to treat wastewater effluent without generating additional waste and to produce an effluent that could be safe for human use and consumption. The solution designed incorporates the phytoremediation capabilities of plants into a novel patent-pending scalable bioreactor (Figure 1). While the foregoing contaminants could be removed with expensive filtration techniques such as reverse osmosis or carbon filtration, these methods still create an additional waste stream which will ultimately end up in a landfill and not foster a circular bioeconomy (Ghosh and Singh, 2005; Le-Minh et al., 2010; Verlicchi and Zambello, 2014). Constructed wetlands, which provided inspiration to our patent-pending hydroponic bioreactor, have been around for dozens of years to treat wastewater effluent. Further, they have been shown to aid in the removal of many of the contaminants of emerging concern through various processes that do not occur in wastewater treatment plants (Ávila et al., 2014; Bhatia and Goyal, 2014; Maine et al., 2007; Özengin and Elmaci, 2016; Verlicchi and Zambello, 2014). Plants, for instance, have been shown to take up contaminants such as pharmaceutical compounds and break them down internally through a process called phytodegradation.

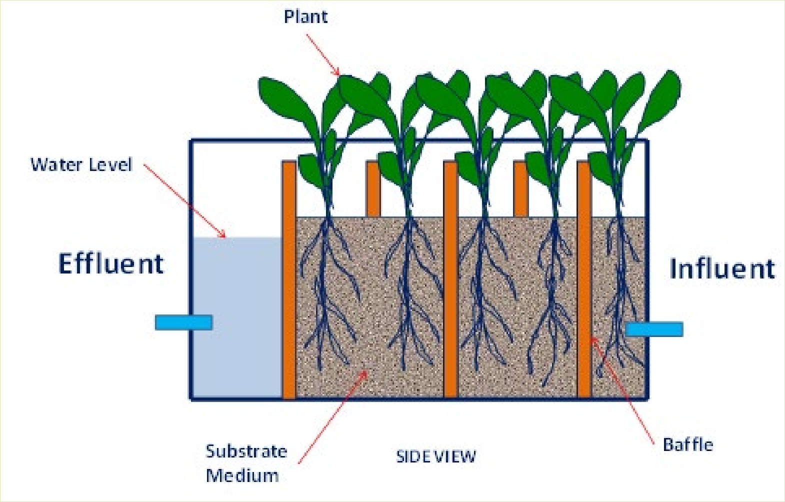

Figure 1. Side-view schematic of the scalable Phyto-Mediated Wastewater Treatment Bioreactor (PWBR) equipped with baffles serving as flow guides to optimize contact between the flowing influent and the plant roots in the substrate (Recsetar and Cuello. 2022).

The treatment capacity and effectiveness of our patent-pending recirculating Phyto-mediated Wastewater Treatment Reactor (PWBR) to remove CEC's from wastewater (Recsetar and Cuello. 2022) was investigated using switch grass, cotton and sorghum growing in a substrate of light expanded clay aggregate (LECA) (Recsetar et. al., 2021) (Figure 2) in a greenhouse at the University of Arizona Controlled Environment Agriculture Center (CEAC).

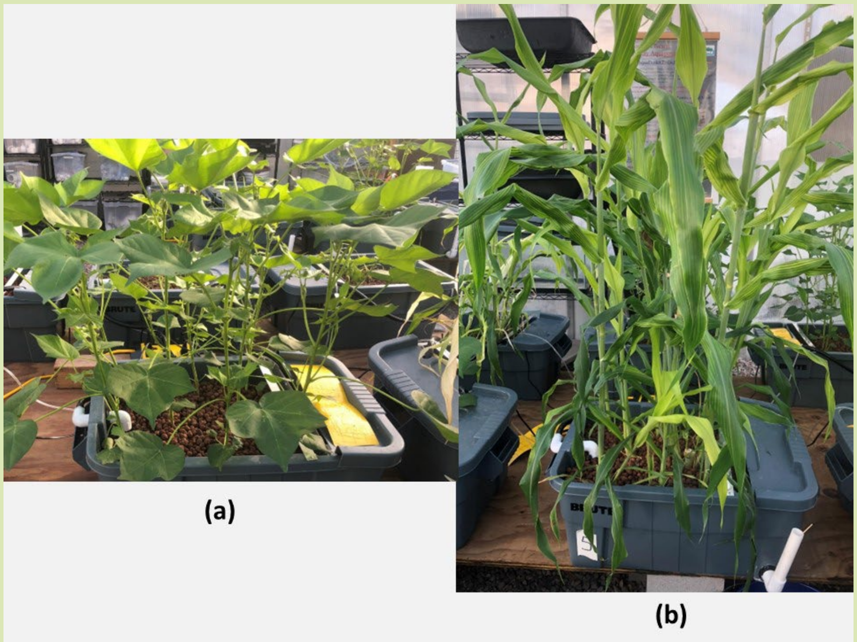

FIGURE 2. EXPERIMENTAL BENCHTOP EMBODIMENTS OF THE PWBR WITH COTTON (GOSSYPIUM ARBORETUM) (A) AND SORGHUM (SORGHUM BICOLOR –CAÑA GANCHADO) (B).

Atenolol, Benzotriazole, Carbamazepine, Hydrochlorothiazide, Iohexol, Iopamidol, Iopromide, Primidone, sulfamethoxazole and Tris (chloropropyl) phosphate (TCPP) were reduced by greater than 80% in all treatments, while the control exhibited little to no removal after 5 days. Indeed, almost every contaminant initially present in the effluent was reduced below detection limits or by >90%. The cotton plants specifically appeared to have been especially effective in treating pharmaceutical compounds, while a combination of the clay substrate and microbiome contributed to reducing the other types of compounds. We believe that industrial hemp could be another valuable industrial crop that would perform effectively in this bioreactor. Thus, the scalable PWBR may be licensed to treat any effluent that contains contaminants of emerging concern that would otherwise enter the environment.

Agricultural applications for PWBR. The PWBR (Recsetar and Cuello. 2022) could be deployed to provide safe water for human use as well as clean water supply for agriculture or aquaculture in various parts of the world. In addition, this technology has applications in arid lands where clean water is a scarce resource. It could also be utilized to treat agricultural effluent from dairy farms, swine farms, or other livestock operations. Further, this scalable technology is relatively low-cost and could have applications in any industry that produces effluent that is not potable and requiring treatment of large batches of water for use in agriculture or aquaculture.

PWBR for Circularity. Treating wastewater effluent using the scalable PWBR has the potential to remove contaminants from our future water supply and produce valuable plant byproducts that can be used to make fibers, concrete, and myriad other industrial products. The PWBR innovation can effectively close the loop on our water use and reuse cycle and has the potential to protect our valuable water supply for years to come.

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6.10 Yuma "Growing Our Own" Initiative

By Tanya Hodges and Baleshka Brenes

In the spring of 2021, the University of Arizona Yuma, partnering with the Greater Yuma Economic Development Corporation, Arizona Western College, Imperial Valley College, the Yuma County Chamber of Commerce, the University of Arizona College of Agriculture and Life Sciences, the University of Arizona Center for Excellence in Desert Agriculture, and the Yuma Fresh Vegetable Association was awarded a USDA-NRCS Collaborative Multistate Grant. This award supported an increase in bachelor's degree attainment and increased skilled and educated labor to support the region's current and future workforce, increasing economic activity driven by research and innovation in the life sciences and biotechnology through advances in engineering, computing, and information sciences, fostering growth in economic development opportunities in Imperial and Yuma Counties. In addition, the NRCS Award enabled the "Growing Our Own" (GOO) Initiative to establish a world-class platform in the desert southwest to support Science, Technology, Engineering, and Math (STEM) workforce development and increase opportunities for entrepreneurial innovation and economic growth. More specifically, the goal is to develop a platform to support and grow current and future Yuma and Imperial counties' Bioeconomy.

Yuma and Imperial Counties are a rich environment for increased bioeconomy and STEM growth. These counties are the "Winter Salad Bowl Capital," responsible for over 90% of North American-grown leafy greens during the winter. Agriculture is the region's primary economic driver, and the region has an important role as part of the international supply chain. A multi-billion dollar agricultural industry, three military bases, and proximity to Mexico provide a rich environment for STEM economies. As Agriculture incorporates artificial intelligence (AI), robotic, automated systems, and precision digital farming, and as Colorado River water becomes increasingly scarce, the region leads in discovering and implementing new desert farming opportunities by identifying new and improved methods of producing more food and bioproducts with less. An increase in bioeconomy and engineering opportunities increases the demand for a skilled and educated labor force to prepare for its role in precision agriculture, biosciences, engineering, and health systems.

The "GOO" Initiative included a four-symposium series, each facilitating events to support STEM talent providers, consumers, and community stakeholders while increasing the region's economic development opportunities. August 2021 kicked off the first symposium, focusing on the region's Engineering & Technology. Over the past 18 months, additional symposiums have focused on the Agriculture and Life Sciences current and future workforce (Figure 2), Ecosystem of Innovation- Brainstorm, and Ecosystem of Innovation Framework/Strategy. Over 400 people attended the four symposiums representing industry, education, and regional government agencies. Most participants came from the greater Yuma region, but the symposiums drew participants from other Arizona, California, Washington D.C., and Maryland areas. The diverse group of participants included industry experts, community and business leaders, educators, and students. Kicking off the symposium series, Deputy Under Secretary for Farm Production and Conservation (FPAC) at USDA, Gloria Montaño Greene, emphasized the importance of a STEM workforce ready workforce. "When considering the workforce's education for agriculture and STEM, we should look at the students and where they are. We should think about how to communicate with them to let them know about the high demand for a technically trained STEM workforce and the abundance of agriculture careers available. All students, from junior high through the postsecondary level, need to be exposed to what is involved in these jobs to attract more young people into agriculture, bioeconomy STEM careers."

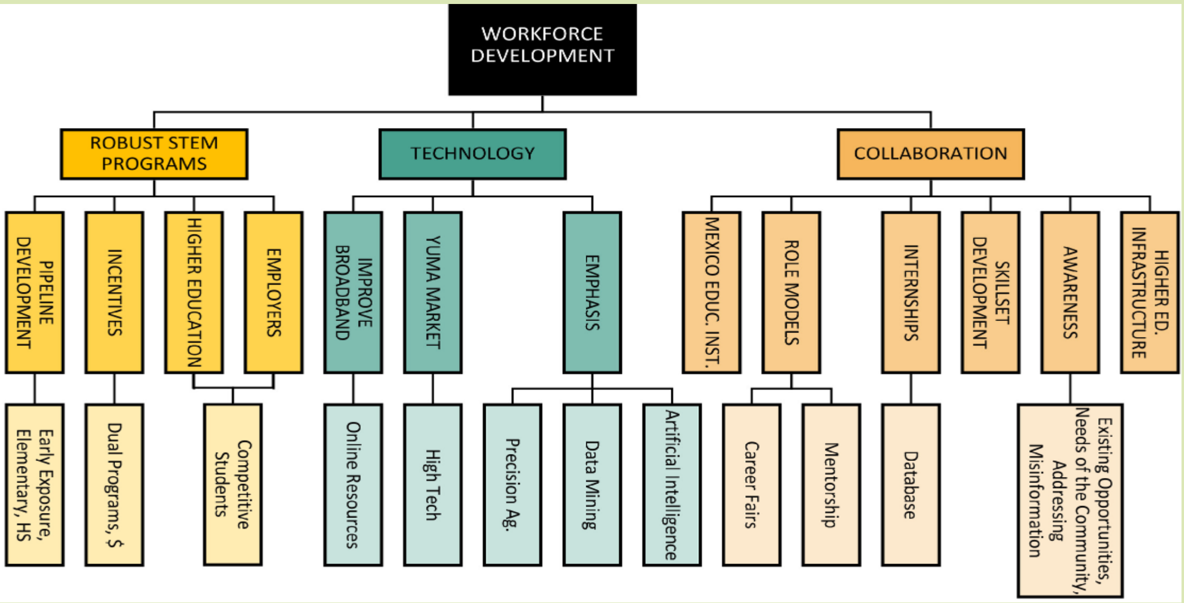

Figure 1: GOO Workforce Development Organizational Structure Emerging Themes

The Ecosystem of Innovation "The Brainstorm" Symposium III and the "Ecosystem of Innovation" Symposium IV "The Framework/Strategies" (Figure 3) provided an organized opportunity to increase the region's collaborative connections and partnerships by defining and developing a strategy to outline what it would take to maximize the benefits of a STEM bioeconomy, identified in a shared sustainable regional plan embraced and supported by industry, agencies, and educational institutions, improving the STEM talent pipeline from early education through professional practice and ongoing professional development.

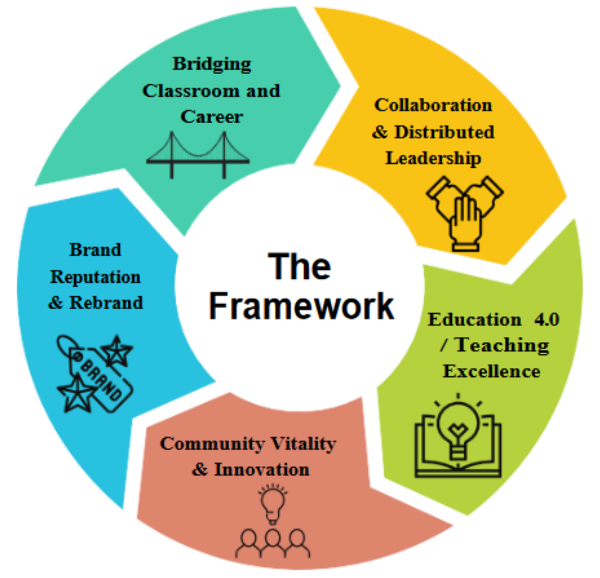

Figure 2: GOO, The Framework supporting a regional sustainable ecosystem of innovation supporting STEM workforce development

Over 45% of the GOO participants indicated they had trouble filling specialty, agriculture, engineer, and biotechnology positions. Addressing these workforce issues, the GOO symposiums provided a platform for identifying challenges, designing strategies, and implementing a sustainable vision for the future. Innovation requires investment in all kinds of capital: financial, social, and human, and requires a continual reinvestment cycle which the "GOO" initiative provides the foundation points for that cycle.

Yuma and Imperial Counties are well situated for economic growth, located next to Mexico and California and close to an international seaport. The first pillar of what an economy is built on is education. Considering all the economic activity in the area, the southwest desert region needs an increase and alignment in this component to grow and expand STEM workforce education. The cooperative extension and the educational mission of the University of Arizona as a land grant university is not just to produce people with degrees but to be an economic development engine, engaging all the stakeholders in the community in that mission. Invention and Innovation are areas in which the university excels. Therefore, bioeconomy development opportunities and growing the STEM workforce will continue to be a top priority. Continued partnerships, such as the one between USDA, Natural Resources Conservation Service (NRCS), industry-supported professional affiliations, other county, state, and federal entities, and the University of Arizona, provide exciting science-based collaboration that provides opportunities for support and demand of a robust trained and educated STEM workforce (Figure 4).

Growing Our Own (GOO) Strategies

Bridging Classroom & Career

Engage students and employers in mutually beneficial opportunities to establish the Southwest Desert Region as a top talent pipeline. Offer the tools, services, and support necessary to empower students and young professionals to reach their full potential and contribute to the region's ecosystem of innovation.

Education 4.0/ Teaching Excellence

Implement a student-centric contemporary curriculum and infrastructure influenced by industry-driven technology and related applied learning to enable students to acquire 21st-century competencies/skills needed to fill the STEM Workforce demands.

Community Vitality & Innovation

Increase the ability of the regional communities to sustain themselves into the future as well as to provide opportunities for its residents to pursue their own life goals and positive life outcomes.

Collaboration & Distributed Leadership

Increase and improve the quality of collaborative efforts through distributed leadership style that promotes a shared and collective movement that is bigger than any person or institution, fostering long lasting significant improvements and capacity for change in our regional communities.

Brand Reputation

Improve the brand reputation of the Desert Southwest Region through community ownership and external exposure to attract and retain talent, ultimately increasing the ecosystem of innovation.

Establishing a world-class platform in the desert southwest to support and increase STEM workforce development.

Figure 3: GOO Strategies supporting a regional sustainable ecosystem of innovation supporting STEM workforce

7. Circular Bioeconomy Opportunities in Southern Arizona

With a robust agricultural system and several agricultural industry clusters throughout the region, Southern Arizona is poised to more actively engage in circular bioeconomy activities and, at the same time, would benefit from introducing circularity into current industry practices. Here, we conclude by considering some opportunities to further develop the region's circular bioeconomy.

The IMPLAN input-output modeling framework estimates how sales from bioeconomy and circular economy industries increase demands for goods and services to those industries. The top industries that provide inputs to the businesses within the bioeconomy are real estate, wholesalers (specifically grocery and other nondurable good wholesalers), logistics and transportation, and other business services such as insurance and employment services. IMPLAN also provides regional purchase coefficients (RPCs) for each industry. RPCs represent that share of local demand that is met by local suppliers. Industries with lower RPCs have relatively low local production relative to overall regional demands on these industries. Low-RPC industries are thus ones where demands are met by "importing" goods and services from outside Southern Arizona. "Imports" as defined here are goods and services sourced outside the region, but not necessarily outside of the United States.

A lower RPC represents an industry that could be targeted by economic development strategies to increase the share of dollars staying within the regional economy. This is called import substitution and would involve the bioeconomy shifting its purchasing from suppliers outside of Southern Arizona to new or expanded suppliers inside the region. Potential industries to target for growth to support and enhance the bioeconomy are those where (a) bioeconomy activity stimulates significant demand and (b) where RPCs are low. These include wholesaling industry, insurance industry, and scientific research and development services. For the circular economy, industries to target for import substitution include warehousing and storage, motor vehicle related wholesaling, business insurance, and employment services.

The case studies highlight the role of the University of Arizona in general and the Division of Agriculture, Life and Veterinary Sciences, and Cooperative Extension (ALVSCE) in particular as innovation catalysts for Southern Arizona. They reflect what Reichert (2019) calls the "central role" of universities in the innovation ecosystem as "orchestrating multi-actor innovation networks." The two main hubs of the region's circular bioeconomy are Tucson and Yuma. The university serves as a conduit for federal R&D funding and local expertise that joins and supports bio-economic activity across these hubs. A key theme amongst nearly all case studies is increasing efficiency and circularity in water use. These case studies illustrate Southern Arizona's potential to be a test-bed for 21st agricultural technologies for arid regions globally. Case studies demonstrate local expertise in controlled environment agricultural (CEA) systems. Such land- and water-saving systems may be transferable to a host of different urban contexts. Applications may even support future space exploration.

Finally, the "Growing Our Own" (GOO) Initiative of Yuma County, Arizona and Imperial County, California illustrates how federal support along with the University of Arizona's Land Grant University infrastructure (human capital, extension resources) can support STEM (Science, Technology, Engineering, and Math) workforce development in rural areas. Rural areas face a "Catch-22" in workforce development. Science-based companies will hesitate to locate in rural areas lacking workers with STEM training. At the same time, students seeking education and jobs in STEM fields often leave rural areas in pursuit of education, training, and jobs. So, potential employers don't come because there are not –high skilled workers and potential workers don't stay because there aren't high skill jobs. The GOO Initiative hopes to replace this Catch-22 with a virtuous cycle of local training and job growth.

8. References

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Appendix

Table A1. Timeline of key policy initiatives and programs to support the bioeconomy

2000	Biomass Research and Development Act directed the Department of Energy (DOE and the Department of Agriculture (USDA) to integrate their biomass R & D. It also established the federal interagency Biomass Research and Development Board to coordinated R&D for bioenergy and other bio-based products. R&D activities included (1) crops and systems that improve feedstock production and processing, (2) converting cellulosic biomass into intermediates for production of biofuels and other products, (3) developing technologies that enhance bio-refinery fuel production, and (4) assessing economic and environmental impacts of biomass technologies.
2002	USDA's BioPreferred® Program was first introduced in the 2002 Farm Bill. With the goal of increasing the development, purchase, and use of biobased products, it requires Federal agencies and contractors to give purchasing preference to biobased products. The USDA BioPreferred® Program also includes a certification and labeling initiative for biobased products.
2010	Memorandum for the Heads of Executive Departments and Agencies, Subject: Science and Technology Priorities for the FY2012 Budget from the Office of Budget and Management (OMB) and the Office of Science and Technology Policy (OSTP) "support research to establish the foundations for a 21st century 'bio-economy.' Advances in biotechnology and improvements in our ability to design biological systems have the potential to address critical national needs in agriculture, energy, health, and the environment." Specifically, agencies were advised to "support research to establish the foundations for a 21st century bio-economy" in areas in which "advances in biotechnology and improvements in our ability to design biological systems have the potential to address critical national needs in agriculture, energy, health and the environment."
2010	USDA Biomass Crop Assistance Program established "to assist agricultural and forest land owners and operators with the establishment and production of eligible crops in selected project areas for conversion to bioenergy, and the collection, harvest, storage, and transportation of material for use in a biomass conversion facility."
2011	America Invents Act of 2011 (P.L. 112-29) addressed barriers that hindered the key industries of biotechnology, medical devices, and advanced manufacturing. The act was intended to accelerate innovation by providing a fast-track patent application process that would allow applicants to obtain a decision within 12 months, reducing the then-current patent backlog and, importantly, moving the U.S. patent system from a "first-to-invent" to a "first-inventor-to-file" system, thereby aligning U.S. patent policies with those of other patent systems around the world.
2011	USDA BioRefinery Assistance Program (renamed the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program in 2014) established to provides loan guarantees to develop, build, or retrofit facilities to produce advanced biofuels, renewable chemicals, and biobased products

Table A1. Timeline of key policy initiatives and programs to support the bioeconomy (continued)

2015	Precision Medicine Initiative established to use biological data and new analytics tools to derive inferences that can be applied to understand disease and develop diagnostics and treatments. Funding to a voluntary national research cohort of a million or more volunteers, scale up identification of genomic drivers in cancer to develop more effective treatments; develop databases to support the regulatory structure needed to advance innovation in precision medicine and protect public health.
2016	Biomass Research and Development Board issued the Federal Activities Report on the Bioeconomy to "emphasize the significant potential for an even stronger U.S. bioeconomy through the production and use of biofuels, bioproducts, and biopower."
2017	The Executive Office of the President released an Update to the Coordinated Framework for the Regulation of Biotechnology aimed at increasing transparency, ensuring safety, streamlining regulatory processes, and accelerating the translation of bio-inventions to market; produced a comprehensive summary of the roles and responsibilities of the three principal regulatory agencies with respect to regulating biotechnology products; summarizes the current responsibilities and the relevant coordination across EPA, FDA, and USDA for the regulatory oversight of an array of biotechnology product areas.
2018	USDA's BioPreferred® Program reauthorized. More than 3,000 companies spanning all 50 states participate in the program.
2019	Office of Science and Technology Policy (OST), "Request for Information on the Bioeconomy," *Federal Register*, vol. 84, no. 175, p. 47561, September 10, 2019. OSTP sought information to, "inform notable gaps, vulnerabilities, and areas to promote and protect in the U.S. Bioeconomy that may benefit from Federal government attention."
2019	White House Summit on America's Bioeconomy held. This included discussion of U.S. bioeconomy leadership as well as opportunities and challenges. Core issues included: (a) identification of critical infrastructure including bottlenecks that hamper innovation or put security at risk, (b) need for training future innovators, and (c) protection of genetic and biological data. Summary of the 2019 White House summit on America's bioeconomy. https://www.whitehouse.gov/wp-content/uploads/2019/10/Summary-of-White-House-Summit-on-Americas-Bioeconomy-October-2019.pdf
2022	Executive Order on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy issued.

Table A.2. Timeline of key publications and reports related to the bioeconomy

1994	Healy, B. On light and worth: Lessons from medicine. Vassar Quarterly 90(4):10–13.
2000	Ernst & Young. The economic contributions of the biotechnology industry to the U.S. economy. http://bei.jcu.cz/Bioeconomy%20folders/documents/bioeconomy/the-economiccontributions-of-the-biotechnology-industry-to-the-u-s-economy
2005	Hevesi, A., and K. Bleiwas. The economic impact of the biotechnology and pharmaceutical industries in New York. New York: Office of the State Comptroller.
2009	NRC report, A New Biology for the 21st Century, describes the growing power of biology, and explains how biotechnology advances and has critical intersections with a number of scientific disciplines, including computing and engineering, addressing a broad range of human needs in such diverse areas as human health, food and nutrition, energy, and the environment. While that report is focused on social benefits, it also points to the deep ties between research innovation and economic benefits.
2012	National Bioeconomy Blueprint laid out strategic objectives that included strengthening relevant R&D efforts, advancing discoveries from laboratory to market, reducing regulatory barriers, developing a 21st-century bioeconomy workforce, and fostering key public– private partnerships. It also highlighted the need to include biotechnology as a key driver of the U.S. bioeconomy strategy. "a bioeconomy is one based on the use of research and innovation in the biological sciences to create economic activity and public benefit."
2014	Carlson, R. 2014. How big is the bioeconomy? Nature Biotechnology 32:598.
2015	Golden, J. S., R. B. Handfield, J. Daystar, and T. E. McConnell. 2015. An economic impact analysis of the U.S. biobased products industry: A report to the Congress of the United States of America. https://www.biopreferred.gov/BPResources/files/EconomicReport_6_12_2015.pdf
2016	Carlson, R. 2016. Estimating the biotech sector's contribution to the U.S. economy. Nature Biotechnology 34(3):247–255.
2016	The U.S. Department of Energy (DOE) and USDA jointly released The Billion Ton Biomass report, providing assessment of the potential to produce 1 billion tons of renewable biomass in the United States for biofuels (including liquid transportation fuels) and biobased chemicals. Report also estimates potential for carbon dioxide reductions and for job creation.
2016	DOE's Bioenergy Technology Office (BETO) also published the Strategic Plan for a Thriving and Sustainable Bioeconomy. The plan identified opportunity areas: (a) enhancing the value proposition of bioenergy; (b) mobilizing the nation's biomass resources; (c) cultivating end use markets and customers; and (d) Expanding stakeholder engagement and collaboration.
2017	National Academies of Sciences, Engineering, and Medicine. Preparing for future products of biotechnology. Washington, DC: The National Academies Press. https://doi.org/10.17226/24605.
2017	The Report of the Task Force on Agriculture and Rural Prosperity made recommendations regarding coordination of federal regulation of biotechnology products, commercialization of biotechnology products and enabling rural use of unmanned technologies; outlining the need to increase public acceptance of

	biotechnology products, modernize and streamline the federal regulatory system for such products, and expedite their commercialization, all of which would improve the bioeconomy through biotechnology
2018	Daystar, J., R. Handfield, J. S. Golden, E. McConnell, B. Morrison, R. Robinson, and K. Kanaoka. An economic impact analysis of the U.S. biobased products industry. https://www.biopreferred.gov/BPResources/files/BiobasedProductsEconomicAnalysis2018.pdf
2018	National Academies of Sciences, Engineering, and Medicine. Biodefense in the age of synthetic biology. Washington, DC: The National Academies Press.
2019	Biomass Research and Development Board issued The Bioeconomy Initiative: Implementation Framework presented goals and actions to address knowledge and technology gaps in: (a) advanced algae systems; (b) feedstock genetic improvement, production, management, and logistics; (c) biomass conversion and carbon utilization; (d) transportation, distribution infrastructure, and end use; (e) bioeconomy analysis, and (f) bioeconomy sustainability.
2020	International Advisory Council on Global Bioeconomy, Global Bioeconomy Policy Report (IV): A Decade of Bioeconomy Policy Development around the World
2020	National Academies of Sciences, Engineering, and Medicine, Safeguarding the Bioeconomy, The National Academies Press, Washington, DC
2020	Release of USDA Science Blueprint: A Roadmap for USDA Science from 2020 to 2025, Washington, DC, https://www.usda.gov/sites/default/files/documents/usda-science-blueprint.pdf. USDA priorities regarding the bioeconomy included (a) promoting bio-based products, (b) developing a bioeconomy research roadmap with short- to long-term goals and metrics, (c) collecting and organizing data for bioeconomy valuation.
2021	Gallo, M.E. The Bioeconomy: A Primer. Congressional Research Service Report R46881, Washington, DC
2023	Bureau of Economic Analysis, U.S. Department of Commerce releases report Developing a National Measure of the Economic Contributions of the Bioeconomy. https://www.bea.gov/system/files/papers/bea-bioeconomy-report.pdf