Federal Sustainable Chemistry Strategic Plan

A Report by the

JOINT SUBCOMMITTEE ON ENVIRONMENT, INNOVATION, AND PUBLIC HEALTH

SUSTAINABLE CHEMISTRY STRATEGY TEAM

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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About the Sustainable Chemistry Strategy Team

The National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2021 (NDAA for FY2021) directed an Interagency Working Group to coordinate federal research on sustainable chemistry. In response, OSTP established the Sustainable Chemistry Strategy Team (SC ST) under the Joint Subcommittee on Environment, Innovation, and Public Health (JEEP) in the Fall of 2021 with the primary purpose of developing this strategic plan.

About this Document

This document identifies federal agency activities that could advance the transition towards a more sustainable chemical future. The NDAA for FY2021 directs OSTP to: establish an interagency working group; develop a consensus definition of sustainable chemistry; perform a landscape analysis of all current federal sustainable chemistry activities; develop a strategic plan to characterize and assess sustainable chemistry; coordinate federal efforts in the areas of regulation, R&D, and challenges; integrate sustainable chemistry into federal R&D through awarded federal grants, prizes, and loans; and increase workforce training and development. OSTP and the SC ST solicited input from the public on critical research gaps and needs for sustainable chemistry through a series of webinars, a Request for Information (RFI) to receive public comment, and comments received from stakeholders. The stakeholder feedback was considered in the development of this report, along with federal agency priorities and programs. Any potential opportunities, commitments, actions, or recommendations discussed in this document would need to be fully vetted through all relevant federal budget, policy, and regulatory processes before being considered for federal adoption or execution and would be subject to available resources.

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The SC ST acknowledges the significant contributions of individuals that served on the Joint Subcommittee on Environment, Innovation, and Public Health (JEEP) and the SC ST. These individuals include:

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Abbreviations and Acronyms

AI	Artificial Intelligence
ATSDR	Agency for Toxic Substances and Disease Registry
CARE	Collective benefit, Authority to control, Responsibility, and Ethics, and their respective sub-principles
CDC	Centers for Disease Control and Prevention
CDOC	Chief Data Officer Council
CEQ	Council on Environmental Quality
DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOL	Department of Labor
DOT	Department of Transportation
EO	Executive Order
EOP	Executive Office of the President
EPA	Environmental Protection Agency
FAIR	Findable, Accessible, Interoperable and Reusable
FDA	Food and Drug Administration
HHS	Department of Health and Human Services
ITA	International Trade Administration
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
NASA	National Aeronautics and Space Administration
NGO	Non-governmental organization
NIEHS	National Institute of Environmental Health Sciences
NIH	National Institutes of Health
NIST	National Institute of Standards & Technology
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OCSPP	EPA Office of Chemical Safety and Pollution Prevention
OMB	Office of Management and Budget
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Administration
OSTP	Office of Science and Technology Policy
R&D	Research and Development
RFI	Request for Information
SBA	Small Business Administration
SBIR	Small Business and Innovation Research
SC	Sustainable Chemistry
ST	Strategy Team
STEM	Science, Technology, Engineering, and Mathematics
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

Executive Summary

The Biden-Harris Administration is committed to delivering clean drinking water, clean air, and safe food to all Americans, including underserved communities. Chemistry impacts the lives of all Americans; a variety of chemicals are used in households, factories, vehicles, and farms to provide the food, water, and products that are used every day. Sustainable chemistry has a multitude of impacts on a daily basis, ranging broadly from transportation to consumer choices. The incorporation of sustainable chemistry principles into U.S. chemical manufacturing helps reduce the environmental and human health impacts of chemical processes and products.

The William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021 (NDAA for FY 2021) required a national coordinating entity for sustainable chemistry, in fulfillment of which the Office of Science and Technology Policy (OSTP) established the Sustainable Chemistry Strategy Team (SC ST) under the Joint Subcommittee on Environment, Innovation, and Public Health (JEEP) of the National Science and Technology Council (NSTC). In August 2023, the SC ST released its first legislatively mandated report, entitled the *Sustainable Chemistry Report: Framing the Federal Landscape*. Within this landscape report, the SC ST described the current science regarding sustainable chemistry, the barriers for advancing innovation in sustainable chemistry, and strategic areas of opportunity to enable more sustainable chemical products and processes. The landscape report laid the foundation and identified opportunities for the development of a federally-aligned strategic plan for sustainable chemistry.

Concurrently, sustainable chemistry solutions can decrease nonrenewable energy demand, expand renewable energy sources, reduce greenhouse gas emissions, improve circularity of products, and enable a secure and sustained production and application of chemicals for critical use.

The NDAA for FY2021 directs the SC ST to develop a strategic plan that identifies "future strategies to avoid duplication of efforts, streamline interagency coordination, facilitate information sharing, and spread best practices among participating agencies." Using stakeholder feedback and interagency discussions, the SC ST developed this federal vision and strategy for supporting the development and implementation of sustainable chemistry products and processes.

This Plan identifies four strategic goals that are supported by the objectives and tasks within the plan:

1) Discovering More Sustainable Chemistry for Future Solutions;
2) Supporting, Building, and Bridging Sustainable Chemistry from Discovery to Commercialization;
3) Promoting Adoption and Growth of Sustainable Chemistry in Business and Subnational Government; and
4) Creating a 21st Century Federal Service for Sustainable Chemistry.

Each of these goals is supported by objectives and tasks. Furthermore, there are five crosscutting themes that are: federal investment into sustainable chemistry, circular economy, data sharing and artificial intelligence (AI) models, environmental justice (EJ) and equity, and education and community engagement. By advancing these goals, tasks, objectives, and crosscutting themes, this strategy identifies opportunities to decrease duplication and increase efficiency as agencies foster the discovery and design of new chemicals and chemical processes, encourage the implementation of more sustainable chemicals and processes, and incorporate the principles of sustainable chemistry into decision making and policies.

Introduction

Chemistry impacts all lives, and a variety of chemicals are used in everyday applications. Sustainable chemistry affects everything from transportation to consumer choices. The incorporation of sustainable chemistry principles into U.S. chemical manufacturing helps reduce the environmental and human health impacts of chemical processes and products. Simultaneously, sustainable chemistries can decrease nonrenewable energy demand, expand renewable energy sources, reduce greenhouse gas emissions, improve circularity of products, and enable a secure and sustained production and application of chemicals for critical use.

The SC ST, under the NSTC/JEEP, was established as required by Subtitle E of the NDAA for FY2021.[3] In response to the mandates from the NDAA for FY2021, the SC ST developed the *Sustainable Chemistry Report, Framing the Federal Landscape*[4] (hereafter referred to as the "2023 SC landscape report") in August 2023 through engagement of various sustainable chemistry stakeholders, a request for information (RFI), virtual workshops, and individual stakeholder meetings. The 2023 SC landscape report addressed the need to propose a consensus federal definition, identified a framework of sustainable chemistry attributes, assessed the status of sustainable chemistry in the United States, and developed a summary of the federal regulations relevant to sustainable chemistry.

Federal Consensus Definition

Sustainable chemistry is the chemistry that produces compounds or materials from building blocks, reagents, and catalysts that are readily-available and renewable, operates at optimal efficiency, and employs renewable energy sources. This includes the intentional design, manufacture, use, and end-of-life management of chemicals, materials, and products across their life cycle that do not adversely impact human health and the environment, while promoting circularity, meeting societal needs, contributing to economic resilience, and aspiring to perpetually use elements, compounds, and materials without depletion of resources or accumulation of waste.

The 2023 SC landscape report also identified key strategic areas that could accelerate innovation and transition to sustainable chemistry: data sharing; standards and metrics development;[5] life cycle assessment; modular design; incentives; education; resource access; alternatives; circularity; and novel methods for hazard assessments.

The NDAA for FY2021 instructed the SC ST to coordinate and support federal work regarding sustainable chemistry and eliminate duplication of federal efforts. As part of this mandate, the SC ST developed this plan, which articulates a federal strategy for advancing sustainable chemistry.

To transform the chemical enterprise into a more sustainable system, the Sustainable Chemistry Strategic Plan identifies goals and objectives that can be achieved through coordinated research,

[3] William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021, (P.L. 116-283).

[4] NSTC: Sustainable Chemistry Report | OSTP | The White House (hereafter referred to as the "2023 SC landscape report")

[5] In this report, the term "metric" is used throughout to represent what is being measured (e.g., body temperature, mass intensity) when communicating sustainability assessments and evaluations. Terminology varies across agencies in the executive branch, and may use different terms to describe metrics, such as indicators, and then the term metric is used to represent the quantified value representing the indicator.

development, and innovation; technology translation and commercialization; workforce development; and stakeholder engagement.

The goals, objectives, and tasks of this strategic plan include actions to be implemented over a range of timeframes. While the plan's objectives and impact could extend over decades, it is flexible and intended to be revisited, evaluated, and reported to Congress every three years until the Sustainable Chemistry Strategy Team terminates ten years after the enactment of the NDAA.[6]

Goals

This Plan identifies four strategic goals that are supported by the objectives and tasks within the plan:

1) Discovering More Sustainable Chemistry for Future Solutions;
2) Supporting, Building, and Bridging Sustainable Chemistry from Discovery to Commercialization;
3) Promoting Adoption and Growth of Sustainable Chemistry in Business and Subnational Government; and
4) Creating a 21st Century Federal Service for Sustainable Chemistry.

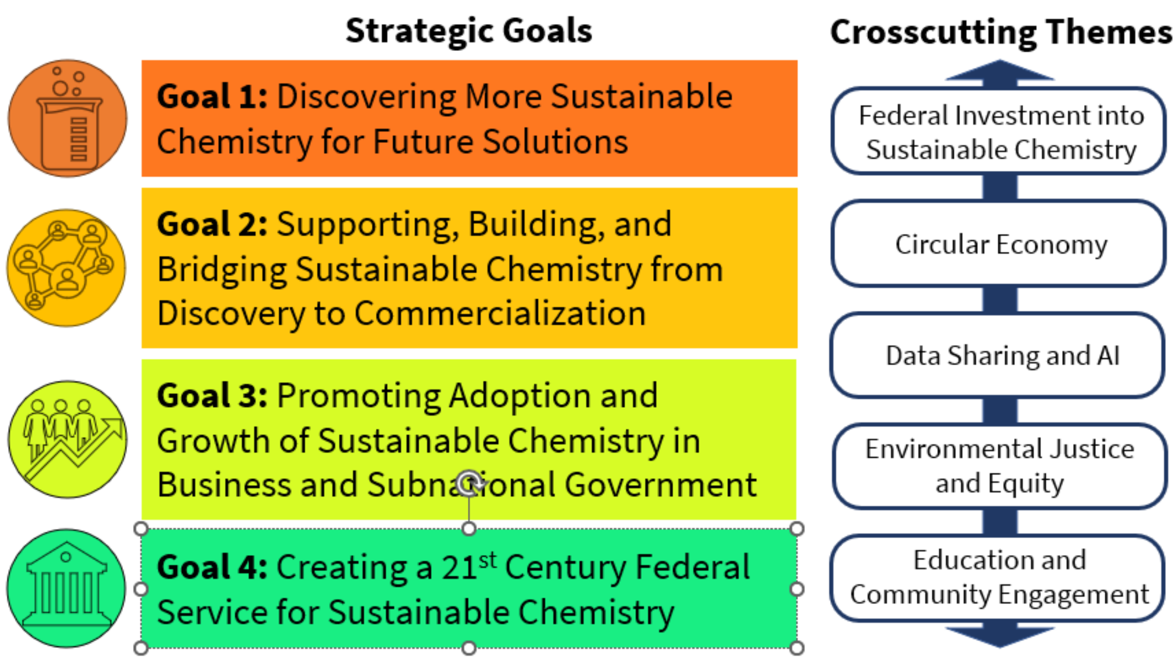

Figure 1. Visual diagram of the strategic goals and crosscutting themes of the strategic plan.

Crosscutting Themes

In addition to the specific goals and objectives that are described in the following strategic plan, there are overarching concepts ("crosscutting themes") that are core to the entire strategy and are interwoven into numerous objectives and tasks. Examples of the crosscutting themes are presented

[6] Per Subtitle E, Section 262(d)(3) of the NDAA for FY2021.

throughout the document and in the summary in Appendix A: Intersection of strategic objectives and crosscutting themes. These crosscutting themes are:

Federal Investment into Sustainable Chemistry

For successful implementation of this strategic plan, it is critical that there be investment in sustainable chemistry by all relevant stakeholders. Federal support for sustainable chemistry could take multiple forms, subject to policy priorities and available resources. An example of federal support could be intramural and extramural funded research and development focused on fundamental insight, discovery and advancement of products, processes, measurements, and data to support and promote sustainable chemistry. Another example could be commitments to engage stakeholders from state, local, Tribal, and territorial communities; academic researchers; non-governmental organizations (NGOs); and industry and trade organizations. Investments can align with federal industrial initiatives, such as activities underway under the Inflation Reduction Act, the Bipartisan Infrastructure Law, and the CHIPS and Science Act. In addition to federal investments, investments by public and private stakeholders are also needed to support the commercialization, adoption, and scale-up processes to advance and deploy sustainable chemistry technologies.

Circular Economy

Sustainable chemistry plays an important role in a circular economy. Recognizing that the term "circular economy" is defined differently across federal agencies, and that it is a rapidly evolving field, some of the terms used in this report may have different meanings to different organizations. Circular economy considerations could include how to repurpose, more efficiently reuse, and recycle materials. Circularity research, materials design and processing, and policies can focus on disposal, recyclability, reusability, degradability and biodegradability, recapture, remanufacture, and recovery of materials. In addition, circularity research, materials design and processing, and policies can include reducing material loss, energy consumption, and polluting effects of current linear practices. These reductions can be accomplished through new approaches based on design for reuse and recycling, from the chemistry and molecular structure of ingredients to efficient value chains that maximize safe retention and return of material in the economy.

Data Sharing and AI

In numerous aspects of the presented strategic plan, the interagency and public availability and accessibility of data, models, and other data tools are needed. Improving the depth, breadth, and quality of Findable, Accessible, Interoperable and Reusable (FAIR) data for many needs could be key to the success of numerous aspects of the strategic plan. FAIR data could inform better decision models, robust and transferable life cycle assessments, greater confidence in labels and claims, and the development of AI models. To support robust and representative sustainability evaluations, it is important to have high-quality data that were developed using criteria complementary to the sustainable chemistry metrics. [7,8] The federal guidance *Advancing Governance, Innovation, and Risk Management for Agency Use of Artificial Intelligence* would establish AI governance structures in federal agencies, advance responsible AI innovation, increase transparency, protect federal workers, and manage risks from government uses of AI.[9,10] The use of AI methods to improve workflow, make predictions, or incorporate diverse aspects of sustainable chemistry present opportunities to leverage existing data to support decisions. It is also essential that model-based uncertainties and testing or validation steps are part of a transparent presentation of AI output.

Environmental Justice and Equity

The Biden-Harris Administration affirmed the importance of EJ for all through Executive Order (EO) 14096: *Revitalizing Our Nation's Commitment to Environmental Justice for All*. Incorporating concepts of EJ and equity under the umbrella of sustainability will be important to guarantee that the benefits of sustainable chemistry are accessible to all people, including reduced adverse health effects and the greater availability of more sustainable products than what is currently available. Efforts in this crosscutting theme should complement the *Environmental Justice Science, Data, and Research Plan*,[11] which provides principles, information, and resources that can assist agencies in advancing the goals of President Biden's executive order. This crosscutting effort includes understanding the disproportionate and cumulative health impacts of less sustainable chemicals and chemical processes on vulnerable populations and communities with EJ concerns. Meaningful involvement in the development of, and equitable access to, more sustainable chemical products and processes can ensure that all communities gain the benefits of these materials.

"Cumulative impacts and their ties to supporting environmental justice principles and stakeholder engagement must also be factors in the prioritization, design, and access to technological advances to avoid a disproportionate burden of chemical hazards."[12]

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[7] Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by Federal Agencies, 67 FR 8452. February 22, 2002. Available at https://www.whitehouse.gov/wp-content/uploads/legacy_drupal_files/omb/assets/OMB/fedreg/reproducible2.pdf

[8] Final Information Quality Bulletin for Peer Review. December 16, 2004. Available at https://www.whitehouse.gov/wp-content/uploads/legacy_drupal_files/omb/memoranda/2005/m05-03.pdf

[9] Office of Management and Budget. 2024. Advancing Governance, Innovation, and Risk Management for Agency Use of Artificial Intelligence. https://www.whitehouse.gov/wp-content/uploads/2023/11/AI-in-Government-Memo-draft-for-public-review.pdf.

[10] EO 14110. Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence. https://ai.gov/ai-use-cases/.

[11] NSTC Environmental Justice Subcommittee. NSTC Environmental Justice Science, Data, and Research Plan. July 2024. https://www.whitehouse.gov/wp-content/uploads/2024/07/NSTC-EJ-Research-Plan-July-2024.pdf.

[12] EPA Office of Research and Development, "Advancing Sustainable Chemistry." March 18, 2024. https://www.epa.gov/system/files/documents/2024-03/fy24-css-star-sustainable-chemistry-rfa-final-march-002.pdf.

Education and Community Engagement

Education and community engagement will be critical to ensure communities and the natural environment benefit from the transition to sustainable chemistries. Improving understanding and involvement in identifying the characteristics and best practices about the concepts, as well as positive scientific and societal impacts of sustainable chemistry, will enable informed consumption of sustainable products and build market interest in more sustainable products relative to what is available today. This effort includes federal agencies incorporating the impacts of sustainable chemistry into communication strategies to the public and advancing the development and identification of tools that can promote sustainable chemistry solutions.

Sustainable Chemistry Framework

As part of the NDAA for FY2021, Congress instructed the SC ST to "develop a working framework of attributes characterizing, and metrics for assessing, sustainable chemistry." Multiple objectives and tasks within this strategic plan are intended to provide data, metrics, and standards that serve as a foundation for the development of a framework to evaluate the sustainability of chemical processes or products; model sustainability metrics for alternative chemical processes or products; and prioritize the research and replacement of more sustainable alternatives. This framework would be developed through the objectives and tasks of this strategic plan, in collaboration with stakeholders from industry, academia, NGOs, and state, local, Tribal, and territorial community members.

Sustainability within chemistry is recognized as being a product of multiple attributes creating a challenge to determine the overall sustainability of a chemical product or process. This strategic plan proposes data, metrics, and other tools that could be incorporated into a framework to enable stakeholders to operationalize the federal consensus definition for sustainable chemistry. A hypothetical application of a potential framework is visually demonstrated in **Figure 2.**

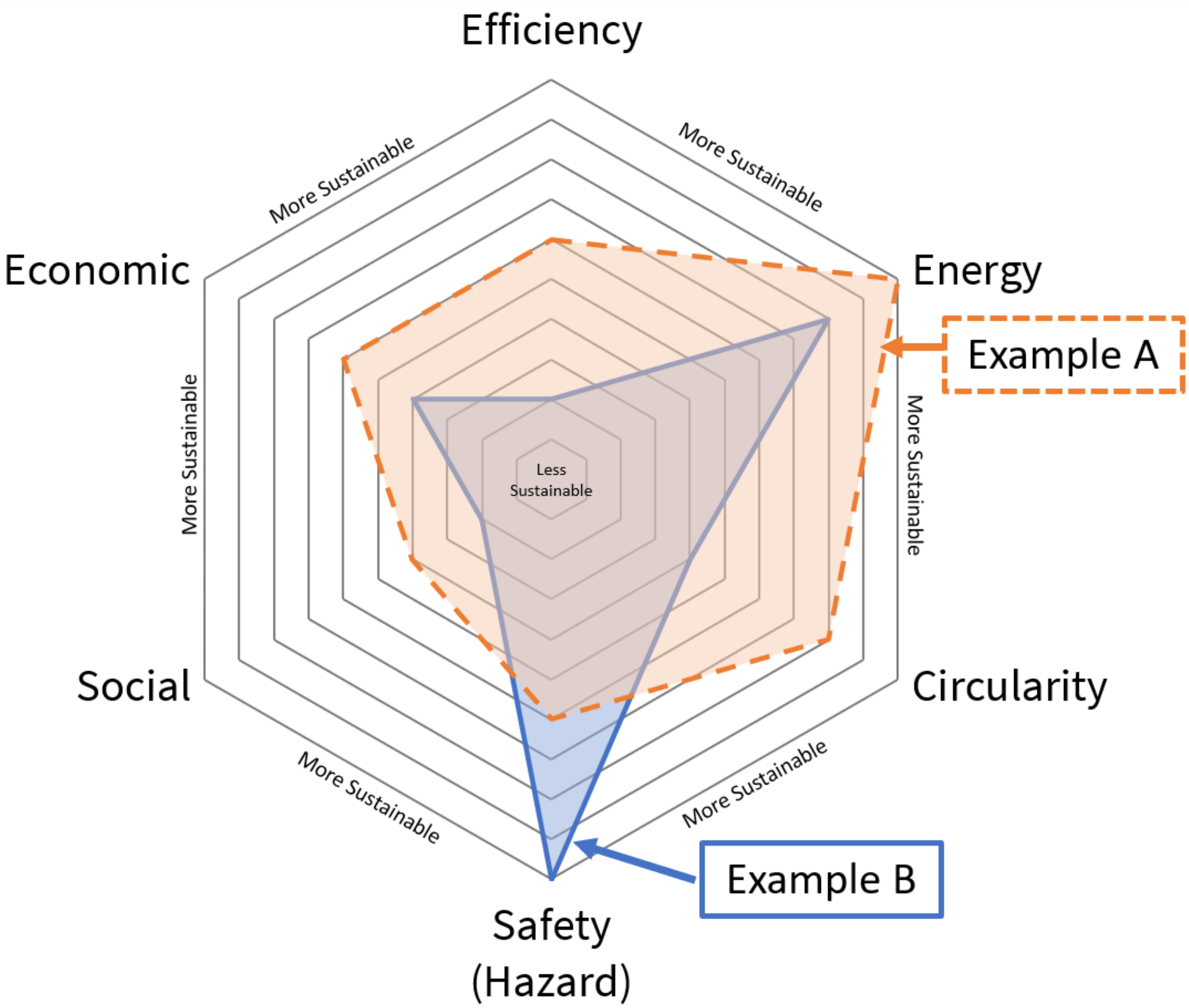

Figure 2. A hypothetical evaluation framework for sustainable chemistry. The two chemical products or processes (Example A and Example B) have different values across six possible sustainable chemistry attributes. Attributes would need to be clearly defined in future federal sustainable chemistry framework(s). Further development could add numerical values that illustrate relevance toward the different attributes. Development of an evaluation framework is an essential tool to assess the sustainability of a product or process so that manufacturers and consumers can make informed decisions.

As metrics and benchmarks for performance are developed and refined for sustainable chemistry, it will be important to incorporate and utilize these metrics in public-private engagement. This engagement can include the generation of new and updated industry and government guidance by agencies on commercial products, such as the use of recycled material or renewable feedstocks for manufacturing. Workplace safety policies and environmental regulations can incorporate sustainable chemistry principles that ensure the safety of workers and communities impacted by the industry. Finally, government policies that impact industry, such as federal procurement, can use sustainable chemistry metrics as part of the prioritization of products and services.

A sustainable chemistry framework could also be used for the prioritization of research and replacement of currently available, less sustainable products or processes. A prioritization scheme within the framework could be developed through stakeholder engagement that focuses on the intersection of sustainable chemistry, contaminants of concern, manufacturing strategy, national security, and supply chains.

GREENSCOPE – An Evaluation Tool for Sustainable Chemistry

EPA's GREENSCOPE tool constitutes an example for the operationalization and quantification of chemical production sustainability. GREENSCOPE quantifies sustainability on a 0-100% scale in four areas; energy, economics, efficiency, and environment using representative indicators and metrics. This tool is designed to directly process specific data into the US Life Cycle Assessment (LCA) Commons Database. It is an example of an evaluation framework that enable manufacturers and could enable consumers to understand the overall sustainability of their chemical product or process.

Goal 1: Discovering More Sustainable Chemistry for Future Solutions

Fundamental scientific research is needed to identify and refine sustainable chemistry solutions for all sectors. This research includes the exploration of fundamentally new chemical bond constructions and reaction modalities, as well as broadening the chemistries available in the marketplace that leverage more sustainable energy sources and materials. Research could include investigating the chemical and physical properties of current, less sustainable materials to identify appropriate, more sustainable alternatives; understanding and addressing the challenges of scaling new chemistries; developing the underlying data needed to evaluate new sustainable chemical products and processes; and identifying technological gaps related to sustainable chemistry challenges. Objectives under this goal can be facilitated by federal and extramural research in alignment with agency programs. However, action in this space cannot be limited to the public sector because solutions will only be as effective as their ability to translate into practice and production. Therefore, any federal investment must be intimately tied to compelling value propositions for stakeholders.

Access to open-source, pre-competitive data from this research will help stakeholders efficiently develop new sustainable chemistry processes and products. Incorporation of data-driven computational methods for designing and evaluating materials could improve efficiency of R&D of new products and processes and the ability to truly design circularity and health protections into new materials.

This goal supports Administration and federal agency priorities, such as alleviating foreign dependence on critical minerals and reducing plastic pollution, and could leverage advances in biotechnology, biomanufacturing, and other technological innovations.[13,14] All of these chemistry priorities contribute towards more sustainable supply chains for Americans. In addition, efforts to prioritize renewable energy sources to drive sustainable chemistry manufacturing, reduction of dependance on nonrenewable starting materials, and an emphasis of waste reduction support the Biden-Harris Administration's goals for decarbonization and taking action on climate change.[15] The expected outcomes of Goal 1 are to accelerate the development of sustainable chemistry processes and products to support and grow the American economy and to protect and preserve the environment.

Given the nature of the research presented in Goal 1, the tasks are not presented in any order to imply timeline or priority.

Objective 1.1: Establish a systems thinking approach for the development of sustainable chemistry products and processes.

Future solutions in sustainable chemistry require systems thinking, which is a scientific approach that considers the interconnectedness of scientific phenomena, products, and processes within a complex environment to reflect what exists and happens in the real world. This includes considering the whole life cycle of products so that new sustainable chemistries are benign-by-design,[16] from the raw material extraction stage to the end-of-life circular economy path. From their inception, new chemicals and materials should be developed emphasizing the use of renewable and local resources; less hazardous chemicals, reactions, and process conditions and locations; sustainable products; and circular supply chains that enable remanufacturing, recycling, and recovery routes. It is important to utilize a systems thinking approach toward sustainable chemistry in the context of the Federal Sustainability Plan.[17] By using a systems thinking approach, proposed sustainable chemistry solutions are better designed and thus able to effectively meet the interconnected needs of diverse stakeholders. This includes efforts such as federal agency initiatives that foster collaboration among industry and local and Tribal communities and Tribal Nations, academia and scientists, subject matter experts, government regulatory bodies, and communities with EJ concerns.

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[13] Interagency Policy Committee on Plastic Pollution and Circular Economy, July 2024. "Mobilizing Federal Action on Plastic Pollution: Progress, Principles, and Priorities."https://www.whitehouse.gov/wp-content/uploads/2024/07/Mobilizing-Federal-Action-on-Plastic-Pollution-Progress-Principles-and-Priorities-July-2024.pdf

[14] Executive Order 14081 of April 27, 2023, "Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy-Request for Information; National Biotechnology and Biomanufacturing Initiative-Measuring the Bioeconomy." https://www.federalregister.gov/documents/2023/04/27/2023-08841/executive-order-14081-advancing-biotechnology-and-biomanufacturing-innovation-for-a-sustainable-safe

[15] Executive Order 14008 of March 16, 2021, "Tackling the Climate Crisis at Home and Abroad." https://www.regulations.gov/document/EPA-HQ-OPPT-2021-0202-0012

[16] Benign-by-design is the concept of creating a new chemical product and/or process that considers three factors: "efficiency of synthetic methodology, economically viable, and environmentally benign". Anastas, P.T. Benign by Design Chemistry. In *Benign by Design*; American Chemical Society, 1994; pp 2-22. DOI: 10.1021/bk-1994-0577.

[17] Executive Order 14057 of December 13, 2021, "Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability." https://www.federalregister.gov/documents/2021/12/13/2021-27114/catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability.

"Creating innovative solutions in the realm of Sustainable Chemistry and successful translation of basic science discoveries to commercialization and wide-spread use requires a paradigm shift where scientific discoveries across disciplinary boundaries must be pursued in the context of functioning systems/models and systems-level approaches. Synergistic cross-disciplinary expertise is expected to open up important new avenues to address these global challenges."[18]

Task 1.1.1: Incorporate the sustainable chemistry framework early in the R&D phase.

Implementation of the sustainable chemistry framework, noted in the introduction, during the R&D phase could help align investment in products and processes that are more sustainable. The framework could enable the identification of sustainable chemicals and materials for new applications, as well as for replacement of less sustainable components in existing applications.

Task 1.1.2: Facilitate new scientific approaches that can aid in using a systems approach for the design of more sustainable products and processes.

Federal agencies could support fundamental scientific research to explore the mechanisms driving multiscale chemical reactions and to understand how the interactions of these processes affect the properties and functions of a complex system. This research could provide the insights for co-design of chemical processes and products and enable a paradigm shift in developing new sustainable chemistry solutions.

Task 1.1.3: Support an interdisciplinary approach toward discovery of chemical alternatives that can reduce or eliminate unintended consequences and regrettable substitutions.

Federal agencies could support studies and scientific initiatives that focus on utilization of renewable resources and reduction of hazardous ingredients, additives, solvents, catalysts, and byproducts. Leveraging the federal government's roles regarding chemical assessment could enable rapid screening of chemicals and materials. This approach could utilize the sustainable chemistry framework to identify the sustainability of a proposed product and prioritize chemicals for sustainable chemistry investments, as well as identify potential hazards early in the R&D process. Examples include the application of benign-by-design principles or development of novel computational toxicology screening tools.

[18] NSF 24-567: Molecular Foundations for Sustainability: Sustainable Polymers Enabled by Emerging Data Analytics (MFS-SPEED). https://new.nsf.gov/funding/opportunities/molecular-foundations-sustainability-sustainable/nsf24-567/solicitation.

Crosscutting Theme: Federal data sharing and chemical hazard models
Sharing of new, or updated, predictive models and their data for determining persistent, bio-accumulative, and/or toxic properties of chemicals can allow federal risk assessors to align their efforts, and it would enable other federal, academic, and industrial researchers to incorporate benign-by-design concepts into their discovery research. In addition, sharing data that were generated in the development of these models is necessary to identify more sustainable chemical alternatives. Examples include EPA's Comptox dashboard and the CPDat database, as well as NIEHS' PubChem.

Task 1.1.4: Identify opportunities that utilize byproducts or waste products for current or new chemical products or processes.

Federally supported R&D could evaluate the incorporation of byproducts or waste products into new chemical products or processes. In addition, federal agencies can establish private-public partnerships focused on the commercial exchange of byproducts, promotion of resource efficiency, and creation of new markets for previously discarded materials. These efforts can provide a path for industries to more easily adopt circular practices. This could include federal initiatives to support research on the use and exchange of byproducts and waste products. Additional research on the use of byproducts and/or waste products can also help to reduce the likelihood of regrettable substitutions and unintended outcomes. See **Figure 3**.

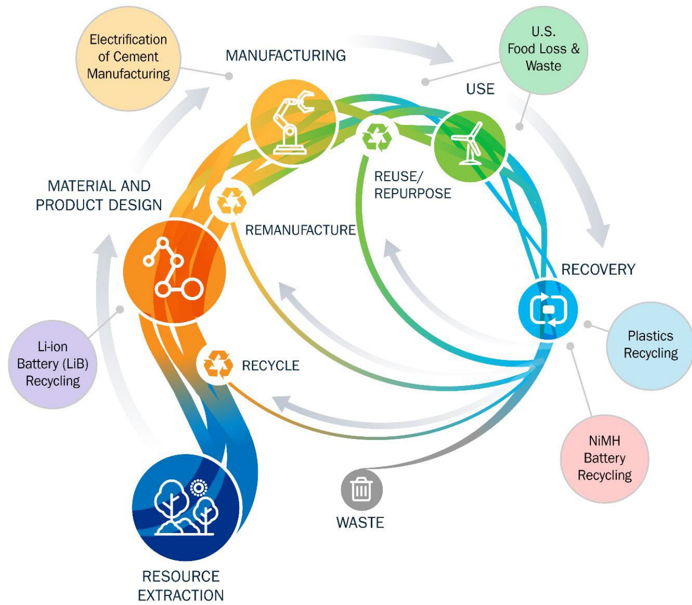

Figure 3. An illustration of the strategies involved in the use of byproducts and waste products (includes agricultural waste and byproducts).[19]

Objective 1.2: Develop and utilize alternative sustainable energy sources to drive chemical processes.

Fundamental science underlies the development of sustainable chemical transformations and chemical manufacturing processes and takes many forms, from determining the appropriate feedstocks to developing new processing pathways. This objective focuses on the drivers for current and not yet known chemical transformations. Despite remarkable gains in the repertoire of known reactions today, most chemical reactions need thermal energy to initiate. Capturing heat from exothermic reactions to power additional work, and reducing or bypassing electricity usage, is one of many approaches that could be taken to develop more sustainable chemistries and processes. There is much room to expand the portfolio of reactions powered by sustainable energy sources, such as geothermal, solar, and wind, for both driving reactions and the manufacturing of constituent materials.

From a sustainable process perspective, an increased understanding of mechanisms associated with energy source, use, efficiency, and recovery can lead to improvements underlying sustainability. Chemical reactions, pathways, and processes need to be energy efficient so that chemical production and use is economically viable, as well as more sustainable. Sustainability also encompasses sourcing local renewable and recycled feedstocks with a low energy footprint to minimize energy requirements and costs associated with resource logistics and transportation. Scientific research can provide the knowledge needed to transform energy mechanisms and advance sustainable chemistry for our Nation's economy and security.

[19] DOE, Office of Energy Efficiency & Renewable Energy, "Sustainable Manufacturing and the Circular Economy." January 2023. https://www.energy.gov/eere/amo/articles/sustainable-manufacturing-and-circular-economy.

Federal Efforts in Sustainable Chemistry

U.S Energy Information Administration has initiated Project BlueSky, "to develop our next generation energy systems model, which will eventually be used to produce the *Annual Energy Outlook* and *International Energy Outlook*. The new model will be designed to address the complexity and interconnectivity of the modern world and the uncertainty associated with markets, technologies, and international trade." The chemical and material industries will be an essential foundation of the systems models.

Task 1.2.1: Explore different types of energy sources that can be channeled into productive reactions.

Federal research can support the development of highly efficient chemical transformations, for instance, by capturing light to drive a chemical process or manipulating chemical bonds using electromagnetic or mechanical forces. Highly efficient chemical reactions can be achieved through improved selectivity and yield, enhanced reaction rates, reduced energy needs, and other approaches. This may be achieved via alternative reaction methods such as electrochemical, microwave, thin films reactions and other field-effect type approaches. The combination of experimental and computational approaches can explore inputs and pathways to determine effective drivers for chemical reactions beyond energy-intensive, high-temperature, and high-pressure conditions.

Task 1.2.2: Reimagine chemical products and processes to create efficient and durable pathways and mechanisms for energy use.

Fundamental science can provide the opportunity to move beyond observed processes in natural and artificial systems and develop innovative new ways to sustainably obtain, store, and distribute electrons, protons, and photons for increased energy efficiency. This can include pathways and mechanisms for energy capture, transduction, storage, and distribution for scalable processes and systems. In addition, research regarding process heating could focus on reducing energy demand and the emissions associated with high-temperature processes.

Task 1.2.3: Harness excess renewable energy by further developing and implementing energy storage techniques.

Research on the integration of more sustainable, alternative energy sources with alternative forms of stored energy could reveal more sustainable pathways for driving chemistry. This can include new research areas such as thermal, chemical, and electrochemical storage, which could include molten salts, hydrogen, and batteries. Several current federal programs aim to develop long-duration energy storage technologies that could be needed as more renewable energy sources such as solar are being deployed.

Objective 1.3: Identify and incorporate sustainable starting materials into chemical processes.

Sustainable feedstocks are derived from multiple sources and will likely be drawn from two major categories in a circular economy. These sources include: (1) feedstocks that are circular by design or recyclable and (2) starting materials that derive from end-of-life materials or waste streams. Many of these resources—biomass, municipal solid waste, and synthetic polymers—consist of complex mixtures. The challenges of using these resources include the ability to selectively extract desired compounds using minimal energy input and to develop efficient, simultaneous recovery of potential components. Approaches for deconstruction of these starting materials must strive to be flexible, both in the inputs used and the ability to tailor products/co-products to desired applications. Furthermore, feedstock conversion ideally would either: (1) directly convert resources to small molecule building blocks to take advantage of well-established and scalable processes or (2) access chemical intermediates that retain some level of complexity and second-life use before eventually being converted into small molecule building blocks.

Task 1.3.1: Continue and enhance R&D emphasis on carbon cycling.

Sustained efforts are needed to convert a range of feedstocks (e.g., biomass, agricultural waste and bioproducts, carbon dioxide, methane, landfill gas, wood waste, biogenic municipal solid waste, food waste, industrial waste, algae) to the chemicals and materials that underpin society. R&D efforts that complement collaborative federal efforts like the National Strategy for Reducing Food Loss and Waste and Recycling Organics could help to advance sustainable chemistry.[20] By developing a suite of versatile technologies, the nation's supply chain could be diversified and provide access to the building blocks and products necessary for modern life. Beyond current products, transformations that provide small molecules or intermediates that can be incorporated into circular processes are also needed. Furthermore, coupling strategies to reduce greenhouse gas emissions with conversion of these molecules to sustainable materials offer an attractive pathway to remove carbon dioxide from the atmosphere and capture carbon dioxide from industrial and electricity production, while providing value-added products.

Task 1.3.2. Expand R&D efforts into circularity beyond carbon.

Consideration of current and potential future challenges, such as resource scarcity and accessibility, is a fundamental component of sustainable chemistry. Exploring and expanding R&D in the circular use of elements other than carbon (e.g., nitrogen, phosphorus, and critical minerals) is prudent to ensuring stability in the nation's agricultural sector and emerging industries that rely heavily on use of metals/inorganics, such as solar panels, wind turbines, and batteries, which are important to meeting net-zero targets. Concurrently, given the growing need for critical minerals and materials in a range of industries, alternative sourcing of these elements and compounds, as well as development of possible alternatives for them, is a growing practical driver of science and technology needs. Alternative sourcing can include

[20] The White House, June 2023. National Strategy for Reducing Food Loss and Waste and Recycling Organics. https://www.whitehouse.gov/wp-content/uploads/2024/06/NATIONAL-STRATEGY-FOR-REDUCING-FOOD-LOSS-AND-WASTE-AND-RECYCLING-ORGANICS_6.11.24.pdf.

using processing approaches such as in situ biogeochemical methods to mobilize, concentrate, and separate minerals. Research and development may result in replacements for these materials or design approaches that minimize or even eliminate their use.

Task 1.3.3: Synergize and enhance resource modeling across existing and emerging sustainable feedstocks.

Understanding the impacts of resource extraction and feedstock procurement, including the human health and environmental effects of resulting chemicals, can lead to better evaluations of overall sustainability of a chemical's life cycle using the sustainable chemistry framework. How biomass and other feedstocks have been used in the past can be helpful information to accelerate gains in other nascent feedstocks. The expected outcome of this task would be the development of models that portray the sustainability of a chemical product or process based on the resource extraction and feedstock procurement.

Objective 1.4: Develop sustainable approaches to address unit operations in chemical processes.

Unit operations are steps within a process that include the transformation of the material, including separation, evaporation, and crystallization. Sustainable chemical conversions require improvements in unit operations within complex systems. This could lead to better management of fluid mechanics, heat transfer, and mass transfer. Sustainable chemical reaction approaches rely on innovations from a unit operations perspective to lower energy and material footprint needs. Effective improvements can result in lower capital and manufacturing costs for chemical reactions and industrial processes, while simultaneously reducing energy consumption, decreasing feedstock demand, minimizing environmental releases, and lowering overall costs. Innovative approaches that enhance the efficiency of unit operations, such as continuous processing and modular systems, also have the potential to result in processes with higher yields, simpler reactions, and reduced energy consumption. These processes transform feedstocks into valuable and cost-effective chemical products more efficiently and reduce environmental impacts. Solutions can build on green/sustainable chemical engineering principles, mass and heat integration for effective resource conservation, recycling, remanufacturing, and utilizing non-traditional mechanisms to improve energy and material conversion efficiency.

Task 1.4.1: Support the development and commercialization of more sustainable unit operations.

Federal agencies can support the design, synthesis, modeling, optimization, and fabrication of more sustainable unit operations as cost-effective alternatives to conventional chemical process unit operations. Also, federal agencies can collaborate with academic and industry researchers to develop common standards and guidelines for evaluating these more sustainable unit operations.

Task 1.4.2: Optimize unit processes to enhance the efficiency of sustainable chemical reactions.

Supporting research, development, and commercialization of efficient mass and heat integration unit processes facilitates effective utilization and conservation of natural resources. Efficient, more sustainable unit processes can maximize the synthesis and production of valuable chemical products, while minimizing waste generation, undesired products, equipment and environmental footprints, and energy consumption. Secondary outcomes include minimizing negative environmental impacts and reducing cumulative impacts on vulnerable communities.

Task 1.4.3: Expand and adopt non-thermal chemical processes to improve the sustainability of unit operations.

Research efforts could lead to the development of unconventional, non-thermal unit operations and industry compliance for liquid-liquid separations, gas phase separations, crystallization, condensation, extraction, flow chemistry, and mass transfer that would incorporate energy/material-saving technologies and run at ambient temperature and pressure conditions.

Task 1.4.4: Support modular, compact, and co-design unit operation technologies and equipment.

Sustainable chemical manufacturing can be enabled through R&D of industrial unit operation equipment and parts that are designed for repairability, recyclability, material recovery, and remanufacturing after end of use. Co-designing for performance and end of life enables circularity through extending service life (refurbishment and repair) and reuse, resulting in capital cost savings, resource efficiency, and minimized demand for fresh materials. Also, regenerative unit operation equipment ecosystems assist sustainable chemical and material manufacturing by creating new business opportunities in a more circular economy.

Objective 1.5: Develop innovative chemical transformations to drive sustainable chemistry solutions.

Efficiency lies at the core of sustainable chemistry solutions and accounts for kinetically and thermodynamically favorable pathways, atom- and step-efficient route and process designs, and the use of readily available and/or easily recyclable products, reagents, catalysts, and matrices. Nature may be taken as an inspiration here, having evolved biocatalytic machinery to generate complex molecular scaffolds from simple building blocks such as carbon dioxide, ammonia, urea, water, and molecular oxygen, in some cases driven by solar energy.

> *"Achieving deep decarbonization of the chemicals sector will require a multidimensional approach, including sustainable feedstocks, low-carbon energy, and advanced unit operations. In all cases, the research phase should incorporate multiple perspectives from the chemical value chain in order to assess required purities, product standards, emissions impact, techno-economics, and scalability from feedstocks to end products."*[21]

[21] DOE Industrial Efficiency & Decarbonization Office, "Chemicals Value Chain Decarbonization: Integrated Solutions for a Complex Challenge." https://www.energy.gov/eere/iedo/articles/chemicals-value-chain-decarbonization-integrated-solutions-complex-challenge.

Similarly, the circularity of the carbon and nitrogen cycles found in nature is instructive. As scientists continue building out fundamentally new transformations, there is still much to learn. For example, it is important to understand mechanism, energy input, and the construction of multiple bonds while minimizing step count, catalyst cost and loading, use of solvent, and byproduct generation. For example, catalysts, reagents, and solvents need to efficiently drive high yield and selectivity in chemical reactions capable of running at optimally efficient conditions (temperature and pressure) to obtain the desired products.

Task 1.5.1: Enhance R&D efforts to explore more sustainable mechanisms for chemical transformation.

Sustainable chemical transformations can take materials traditionally considered waste and convert them into useful renewable feedstocks for new chemicals and products. Sustainable chemistry would benefit from a better understanding of the step-by-step mechanisms underlying chemical transformations, providing knowledge into how best to access new pathways of reactivity and drive chemistries with sustainable energy sources. These mechanisms include light-driven chemical processes, electrochemical processes, and other types of stimuli-response driven reactions. Reduction-oxidation reactions continue to rely significantly on less sustainable chemical reagents such as heavy or precious metal complexes. These reaction methods introduce significant economic and environmental burdens into chemical processes. Continued research can provide the knowledge and tools to develop sustainable electrocatalytic chemistries and electrode materials and address challenges of scalability of solar and electrochemical processes. The need to explore these fundamental chemical mechanisms may require advances in characterization tools.

Task 1.5.2: Continue to drive innovations in earth-abundant metal catalysis.

The shift toward more sustainable energy inputs and low-carbon processes could affect the catalyst composition/structure and the elements that will be used to form them. A notable research challenge is the development of inexpensive metal alternatives to replace the more commonly used and generally more expensive and scarce transition metal catalysts. In addition, national security concerns regarding the current demand for critical materials could be addressed in part through research in pursuit of new formulations and innovations for catalyst designs that remove the need for critical materials.

Task 1.5.3: Support innovation and adoption of biocatalysis and synthetic biology for chemical development and manufacturing.

The fields of biocatalysis and synthetic biology seek to harness the power of enzymes, hybrid biocatalytic/chemocatalytic methods, and enzymatic cascades, as well as whole cell and fermentation pathways for synthetic chemical processes. This effort is in alignment with the

Administration's priority of advancing biotechnology and biomanufacturing,[22,23] which embraces the interconnectedness of biological reactions in a complex system (i.e., systems thinking). Research in biocatalysis—both how it works naturally and how it can be modified for specific chemical transformations—could provide innovative new approaches for sustainable chemistry.

Objective 1.6: Leverage data-driven approaches to advance sustainable chemistry practices.

Advances in sustainable chemistry may require the development of new data science and automation technologies to interrogate, analyze, and predict the outcome of chemical processes. Ultimately, this could enable the chemical development and manufacturing pipelines to be streamlined. These advancements could shorten time to market for new small molecules and materials, mitigate waste streams through the parallelization, miniaturization, and automation of reaction discovery, increase the efficiency and predictability of chemical manufacturing, and work synergistically with human ingenuity to drive innovation. Recent advancements in AI models have shown the promise of this interplay across multiple arms of the chemical enterprise, but significant challenges remain to harness the full potential of this platform. Effective strategies may engage experts and resources across multiple fields (e.g., chemistry, data science, computer science, engineering, robotics, public health) and federal and non-federal organizations. See Appendix B: Federal opportunities for the development of data sharing tools for additional information.

Task 1.6.1: Invest in the development and innovation of chemistry-focused AI models for sustainable chemistry solutions.

Through the combination of advances in high-throughput experimentation and AI-algorithms capable of processing and predicting from large data sets, the process of chemical discovery can be enhanced beyond human-driven experimentation alone. That said, there is a need for a scientific cultural shift to capture more comprehensive data for both successful and less successful catalytic and synthetic transformations. This will integrate chemical knowledge based on human intuition and provide a much stronger and deeper foundation for AI-based tool-building in this space. Scientific exploration involves the investigation of new, unexplored chemical spaces and generates large, disparate, and multi-dimensional data sets, features that present significant challenges to traditional AI algorithms. The ability to extract value from inherently smaller sample sizes is also valuable, as certain areas of study may always be data-constrained, and it is important to have the ability to model these phenomena more effectively using AI models. Continued efforts are needed to develop or adapt learning models specifically for the purpose of driving chemical innovation.

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[22] White House Office of Science and Technology Policy, "Bold Goals for U.S. Biotechnology and Biomanufacturing." March 2023. https://www.whitehouse.gov/wp-content/uploads/2023/03/Bold-Goals-for-U.S.-Biotechnology-and-Biomanufacturing-Harnessing-Research-and-Development-To-Further-Societal-Goals-FINAL.pdf

[23] White House Office of Science and Technology Policy, "Building a Vibrant Domestic Biomanufacturing Ecosystem." November 2024. https://www.whitehouse.gov/wp-content/uploads/2024/11/BUILDING-A-VIBRANT-DOMESTIC-BIOMANUFACTURING-ECOSYSTEM.pdf.

Task 1.6.2: Drive advances in autonomous AI-driven chemical discovery processes.

AI and automation could accelerate chemical discovery by increasing the number of samples and pathways examined in a time period compared to the typical manual process. Incorporation of sustainability metrics into autonomous AI-driven chemical discovery could enable a more efficient and sustainable process to discovering future sustainable chemistry solutions.

Task 1.6.3: Create crosscutting data-networks and repositories of large data sets.

A central challenge in leveraging data science for the advancement of sustainable chemistry is the diffuse and diverse pieces of data needed to effectively interrogate a system (e.g., chemical structures, reaction parameters, reagent sources, and process time stamps). Crosscutting data-networks and repositories populated with high-quality and standardized data sets can reduce duplicative research efforts and enable faster progress through the study of consistent and harmonized scientific information, contributing to the development of innovative sustainable chemistry solutions. Sustaining these networks and repositories can be a challenge but may reduce duplicative research efforts. Data generated should conform to FAIR Principles to guarantee the usability of the data by broad researchers.

Task 1.6.4: Develop datasets and tools that enable comprehensive assessment models.

Comprehensive models that assess hazard and environmental impact, including those that incorporate the potential impacts to vulnerable and/or susceptible subpopulations, allows researchers to use a holistic approach for understanding the inputs and outputs, and their respective impacts, of manufacturing processes and products. Generating data intended to inform comprehensive assessment models can identify areas for improvement and enable chemical manufacturers, city/state governments, and other organizations to make informed decisions on chemical process modifications. For example, life cycle assessments (LCAs), such as datasets available through the Federal LCA Commons that span multiple agencies' data repositories or the Denix LCA used by DOD, can enable researchers to assess the environmental impact of chemical products and processes from cradle to grave.[24,25] Different federal agencies offer individual LCA tools, and LCA methodologies are being implemented across sectors; however, there is a need to develop data standards and expand a portfolio of case studies relevant to chemical synthesis and end use.

Task 1.6.5: Advance tools to monitor and illuminate complex chemical reactions.

Monitoring changes in the catalyst structure, the intermediates produced during a chemical reaction, and the product distributions over time and under operating conditions can reveal key steps of the reaction mechanism and help improve the reactivity, selectivity, and durability of next-generation, sustainable catalytic systems. Interrogating these reactions depends on both the development of new characterization techniques and the ability to process or model

[24] Federal LCA Commons, "Federal LCA Commons." https://www.lcacommons.gov/.

[25] Department of Defense, "Denix: DOD's Platform for Installations, Energy, Environment, Safety & Occupational Health Information." https://www.denix.osd.mil/.

data in real time, which relies on advances in computing and data science. In addition, sharing datasets and methods across the scientific community to inform innovative computational models can provide more complete pictures of how chemical reactions proceed and can be further improved.

Goal 2: Supporting, Building, and Bridging Sustainable Chemistry from Discovery to Commercialization

Even with future technological advancements, sustainable chemistry will need to demonstrate performance at a commercial scale to gain traction and broad implementation. Modes of linear manufacturing, consumption of resources, and multiple waste stream generation need sustainable transformations. These can be driven by investment in and support for novel business models, incentives, and infrastructure that lower barriers to adoption and prioritize a circular system.

Priorities and investments in the application of scalable sustainable chemistry are needed to maintain and return natural resources for the benefit of society, including future generations. Challenges are already associated with the transition between discovery and implementation, and then scaling up sustainable chemistry from bench to industrial processes without a set of well-defined metrics for success makes this concept even more difficult to attain. Achieving a sustainable future will require the development and utilization of sustainable technology and more complex/comprehensive models for risk mitigation, management, and resilience. This allows for a better assessment of a product's sustainability, facilitate transition from discovery through commercialization, and inform better choices. Tools such as decision support, transparent and representative metrics, and sustainability-centered standards could drive the economy towards adopting sustainable chemistry solutions. The expected outcome of Goal 2 is to facilitate transitions from discovery though commercialization to enable more American companies to adopt novel sustainable chemistry products and processes.

The tasks under each objective in Goal 2 are presented in relative order of the expected timeline for completion, without implying interdependency or prerequisites to execution. The initial tasks within an objective are more near-term tasks, and the latter tasks within an objective are long-term tasks.

Objective 2.1: Motivate the chemical sector to converge towards key technical challenges of scaling up sustainable chemistry solutions.

R&D roadmaps and gap analyses, from fundamental science to adoption and application, are vital to identifying and understanding the key technical challenges to adopting sustainable chemistry. Public-private partnerships are important to integrate private sector needs and experiences and inform public action. These insights could lead to interim checkpoints to help guide progress in sustainable chemistry. An iterative process with ongoing dialogue among communities (including those with EJ concerns), industry, and government would be helpful so that government agencies can help mitigate pitfalls. The process to identify and understand the key technical challenges in adopting sustainable chemistry solutions should be flexible and adaptive.

Task 2.1.1: Collaborate with existing programs and partnerships and encourage industry to share barriers to adopting sustainable chemistry processes and products.

Adoption of sustainable chemistry requires methods to better understand the industry landscape and existing barriers to implementation that must be overcome. One of the tools the federal government could employ to help prioritize investment for greater sustainable chemistry impacts is to encourage industries to share R&D roadmaps about future challenges from fundamental science to application. This task could allow industry, the public (especially members of communities with EJ concerns), and government agencies to collaboratively define endpoints. Sharing R&D roadmaps can also help to identify a platform for continuous improvement as industry and government strive towards more sustainable practices, while preventing harm to people disproportionately burdened by any negative impacts of chemical production.

Federal Efforts and Collaborative Opportunities in Sustainable Chemistry

Collaboration with private stakeholders and project developers can provide insights in new tools to actively address more sustainable chemistry processes and products. An example is the private stakeholders and project developers that apply to the Biorefinery, Renewable Chemicals, and Biobased Product Manufacturing Assistance Program. These partnerships can help federal agencies better understand the challenges of bringing new and emerging chemical products to market. Stakeholders at the forefront of the R&D and production ecosystem can partner with federal agencies to identify roadblocks that hinder the effective deployment of sustainable chemical technology. Incorporating feedback and commentary from these entities can inform and address regulatory actions to help more American projects succeed.

Task 2.1.2: Create Federal Sustainable Chemistry R&D Roadmaps for different industrial sectors with integrated stakeholder engagement.

Establishing a R&D feedback loop with comprehensive stakeholder engagement will be critical to advancing sustainable chemistry goals and ensuring that the questions and needs of various communities are addressed. Stakeholder groups include scientific researchers, NGOs, industry sector representatives, trade associations, and the public (especially members of communities with EJ concerns). Engagement could include direct communication through individual interactions, community listening sessions, and/or potential larger collaboration "summits" where federal representatives and stakeholders come together virtually or in-person to discuss opportunities, challenges, and potential roadblocks for advancing sustainable chemistry practices and products. Mechanisms for communication may vary depending on the audience, but, regardless of the mechanism, a federal program that facilitates hybrid stakeholder engagement could play an important role in helping to solve sustainable chemistry relevant problems.

Task 2.1.3: Promote and leverage existing certification and standards programs to create paths to expand capacity and create opportunities for new entrants and new sectors.

Existing programs can be leveraged to engage and motivate stakeholders in adopting sustainable chemistries. For example, the Environmental Protection Agency's (EPA) Safer Choice program[26] certifies products containing safer ingredients and works in partnership with industry to advance additional aspects of sustainable chemistry. Current certification programs could also be used to expand capacity, for example expanding product range to new sectors.

In addition to expanding certification programs, programs can be leveraged to recognize the areas of notable progress. For example, the United States Department of Agriculture's (USDA) BioPreferred certification program encourages and supports sustainable chemistry, and the EPA Safer Choice Partner of the Year Awards recognize the leadership contributions of partners and stakeholders who have shown achievement in the design, manufacture, promotion, selection, and use of products with safer chemicals over the past year.[27,28]

Task 2.1.4: Facilitate broad-scale data sharing of scientific industry knowledge and technical expertise as a public goods resource.

Limited complete and robust data regarding scaling processes is one of the immediate barriers to the transition towards a sustainable chemical future. The federal government could facilitate the broad-scale data and scientific knowledge sharing without taking away an organization's competitive edge. Significant federal investments would potentially be required to accomplish this task, including building, staffing, and maintaining a process and system that encourages this information sharing.

Crosscutting Theme: Environmental Justice and an R&D Roadmap for Sustainable Chemistry

In the development of an R&D roadmap for sustainable chemistry, it will be essential that federal agencies include stakeholder engagement with diverse populations. These efforts should align with the 2024 Environmental Justice Science, Data, and Research Plan. It is of great importance that populations disproportionately affected by environmental and health issues have opportunities to co-develop science, data, and research processes relevant to sustainable chemistry. Their unique perspectives promote the just interpretation of results in ways that identify and address systemic inequalities and biases, and ensure that the findings are accessible and actionable.

[26] U.S. Environmental Protection Agency, "Safer Choice." https://www.epa.gov/saferchoice.

[27] U.S. Environmental Protection Agency. "Safer Choice Partner of the Year Awards." https://www.epa.gov/saferchoice/safer-choice-partner-year-awards.

[28] U.S. Department of Agriculture, "BioPreferred." https://www.biopreferred.gov/BioPreferred/.

Objective 2.2: Support the development and adoption of comprehensive decision models, metrics, and data management systems to evaluate sustainable chemistry processes and products.

High-quality decision models assist in the construction of steps or plans to achieve a goal, while also enabling progress assessment. Developing comprehensive decision models requires coupling of life cycle and technoeconomic analyses to understand the full effects. There are opportunities to expand existing decision models within the realm of and that better support sustainability in chemistry, chemical manufacturing, and local infrastructure. The federal government can facilitate the utilization of both national and international standards to create a representative, comprehensive, and interdisciplinary decision model. With assistance and guidance from the public, industry, and academia, this model could promote certain outcomes from sustainable chemistry such as sustainable transportation, manufacturing, agriculture, energy, and environment.

This model could include all data types relevant for life cycle assessment. Additionally, manufacturers could voluntarily share information while respecting intellectual property rights. For example, they could volunteer hazard properties, chemical properties, and impacts on communities with EJ concerns to advance sustainable chemistry and EJ. Initial evaluation of products using sustainability metrics would serve the purposes of developing a baseline understanding of the sustainability of current market offerings. Volunteering data on environmental release and exposure throughout the product's life cycle could help generate a more realistic understanding of sustainable chemistry in practice. Standardized methods for the evaluation of metrics reached through consensus of governmental and NGOs can lead to widespread adoption and enable comparability of data generated by different organizations.

Task 2.2.1: Develop sustainable chemistry decision models to help guide industry towards sustainable chemical solutions.

Currently, decision models are influenced by three encompassing factors: economic feasibility, technological feasibility, and time constraints. To help manufacturers and consumers make better decisions, there needs to be a cultural shift that prioritizes sustainable chemistry outcomes. The use of the sustainable chemistry framework to develop decision models could enable industry to adopt a culture of sustainable chemistry, setting targets that minimize or eliminate waste and hazards, exploring sustainable alternatives, assessing the incorporation of sustainable resources in manufacturing processes, and considering end-users' waste and recycling practices.

Task 2.2.2: Develop interagency aligned metrics for understanding the factors to evaluate sustainable chemistry and minimize unintended consequences.

There are multiple factors to consider during decision-making based on the definition of sustainable chemistry. Such considerations require a process and tools for government and industry to assess the extent to which a product achieves sustainable chemistry aims. The collaborative development of benchmarks and metrics can be incorporated into the sustainable chemistry framework to enable evaluation of the sustainability of a chemical product or process to help industry and consumers make informed decisions.

> *"The goals of informed substitution are to minimize the likelihood of unintended consequences, which can result from a precautionary switch away from a chemical of concern without fully understanding the profile of potential alternatives, and to enable a course of action based on the best information—on the environment and human health— that is available or can be estimated."*[29]

Task 2.2.3: Develop an approach and metrics for sustainable chemistry data generation and sharing.

The transition towards more sustainable chemistry requires a fundamentally new approach. The first step will be developing metrics for data generation and sharing through joint efforts between the federal government and stakeholders. These metrics need to clearly communicate efficiency, energy, circularity, safety (hazard), social, and economic impacts, among other attributes. Such metrics should be easily usable by the private sector, government purchasers, and investors. Furthermore, these metrics could build on the work of existing programs that have already been developed. Additionally, the government may need to invest in and foster the development of an infrastructure to enable interoperable, diverse, high-quality data for use in sustainability evaluations.

Federal Efforts in Sustainable Chemistry

The Federal Trade Commission (FTC) regularly issues Green Guides, aimed to help companies that market "green" products to avoid making environmental claims that mislead consumers. The Green Guide provides recommendations on the use of terms and concepts such as "Carbon Offsets," "Compostable," "Non-Toxic," "Recyclable," and "Ozone-Safe and Ozone-Friendly." These efforts could be adapted to incorporate sustainable chemistry principles.

Task 2.2.4: Develop an interoperable data collection and management system to support stakeholders in evaluating sustainability of chemicals or products.

Appropriate agencies could take responsibility for developing and maintaining a data collection and management system. Voluntary data submission from industry could help to better inform these models for real world applications. Once an interoperable data collection and management system is developed and implemented, the government could ensure the protection and integration of available data and tools to support stakeholders in evaluating the sustainability of a chemical or product. Data gaps should also be highlighted for future data generation. Over time, the development of robust sustainable chemistry data sets could help

[29] EPA Office of Pollution Prevention and Toxics, "EPA's Safer Choice Standard (formerly, the 'DfE Standard for Safer Products')." February 2015 https://www.epa.gov/sites/default/files/2013-12/documents/standard-for-safer-products.pdf.

to inform future improvements with sustainable chemistry metrics. Increased data transparency could also enable more informed, and hopefully more sustainable, transactions.

Task 2.2.5: Develop online tools for stakeholders to easily convey sustainable chemistry evaluation metrics for a given product.

Freely available online tools could be developed and made broadly available to allow stakeholders to easily evaluate ingredients, products, and processes in terms of sustainable chemistry evaluation metrics. These tools could contain a database relevant to the generation of sustainability metrics. The databases could be assembled to enable sharing of public data amongst government agencies and industry groups, while protecting sensitive business information. The tools could be designed to automatically generate a report of high-level sustainability metrics for the desired list of products/ingredients.

Federal Efforts in Sustainable Chemistry

EPA's Safer Choice program has compiled the Safer Chemical Ingredients List (SCIL) using a functional class approach. Safer Choice focuses its review of formulation ingredients on the key environmental and human health characteristics of concern within a functional class. This approach allows formulators to use those ingredients with the lowest hazard in their functional class, while still formulating high-performing products. Other examples of online resources include EPA's ChemView and the USDA's BioPreferred program that easily conveys biobased products to consumers is the BioPreferred program.

Task 2.2.6: Develop a sustainable material database and corresponding government-supported website that has a freely accessible list of chemicals and polymers with their sustainability metrics.

There may be a need for a database and public facing website that lists materials with their sustainability evaluation, their potential or known applications, and explanations about their relative performance and sustainability compared to other chemicals used in that application space. Clear guidance or criteria presented from the sustainability framework could be developed to compare the sustainability of materials. Government chemical databases could also be connected to that website to provide centralized information on toxicity and environmental information on each chemical. Databases that identify the properties of these chemicals and polymers could be provided, including gaps in information for complete risk characterization of materials. Key publications and resources could be linked to each of these chemicals to provide interested stakeholders information that is required to support sustainable chemistry decisions. Challenges may exist around the availability and sensitivity of these data, and additional work will need to be done to identify what could, can, and should be available on an open access platform.

Objective 2.3: Facilitate and accelerate the sustainable chemistry transition from discovery to implementation.

Laboratory or pilot-scale technologies for more sustainable products can be hindered from implementation due to the difficulty converting the technology to a production scale. Access to sustainable energy and reagent material, modifications of current manufacturing equipment, and efficient production of products to meet demand are some barriers that limit scaling of sustainable chemistry technology. There are several opportunities for government contribution to the research and support mechanisms to accelerate the sustainable chemistry solution transition into commercial applications.

Task 2.3.1: Support research in scalability of sustainable chemistry technology.

Research regarding the scaling of processes from bench to commercial production could enable manufacturers to overcome barriers to implementation. For example, research in scale up of biomanufacturing processes could address issues of reproducibility and productivity in these inherently complex systems. Also, additional research could support the development and application of sensors to monitor scaled processes, including in larger reactors. The ability to take continuous and periodic measurements of key parameters can support more sustainable manufacturing. The development of cost-benefit models that include the cost of scaling and the benefit of a more sustainable, equal, or higher performing process will allow stakeholders to better understand and implement scaling technologies.

Task 2.3.2: Develop a public platform for sharing success stories about approaches, tools, and data for implementing more sustainable chemistry processes and products.

A centralized repository or platform could share case studies of technologies that can be applied across diverse products. These examples could be used by manufacturers to identify successes for going from fundamental scientific research to initial applications for a more sustainable technology.

Task 2.3.3: Utilize federal government funding mechanisms and programs to support the transition of sustainable chemistry technologies.

The federal government has both intramural and extramural funding mechanisms that could support the R&D to transition sustainable chemistry from the experimental (lab) phase to industry/commercial interest. The extramural funding vehicles commonly used for R&D include research grant funding, Small Business Innovation Research and Small Business Technology Transfer programs, planning and demonstration grants, implementation grants, cooperative R&D agreements, materials transfer agreements, and centers of excellence programs. Other government spending vehicles that may help support the sustainable chemistry transitions include government contracts and acquisitions, prize competitions and challenges, government-sponsored consortia for precompetitive work, and federal applied loan programs. For example, the Biorefinery, Renewable Chemicals, and Biobased Product Manufacturing Assistance Program (9003) could be leveraged to promote the development and production of sustainable and renewable chemicals from biomass feedstocks. All government funding would be subject to available resources.

Federal Efforts in Sustainable Chemistry

Recent General Services Administration efforts have highlighted the federal government's role in prioritizing more sustainable options for products, including prioritizing the federal purchasing of cleaning products that do not contain PFAS and the use of $23.8 billion to improve the sustainability of federal buildings across the U.S. In addition, the DOD has established the Sustainable Products Center, which provides an "informational repository for results, success stories, technical data, and lessons learned from sustainable technology and product demonstrations conducted at DOD installations."

Goal 3: Promoting Adoption and Growth of Sustainable Chemistry in Businesses and Subnational Governments

There are opportunities for the federal government to accelerate the transition to more sustainable chemical products and processes. The 2023 SC Landscape Report described the many roles of the federal government in encouraging the use of sustainable chemistry practices and manufacturing of sustainable products, including the role of the federal government as a regulator, market facilitator, and consumer. With the aim of creating a supportive policy environment, the federal government can identify which existing policies and programs are most catalytic in terms of facilitating innovation and investment, as well as when new approaches may help the scale up of new and more sustainable practices. As a market facilitator, the federal government can support the creation of innovative ecosystems in which stakeholders can collaborate to develop and scale new practices, as well as managing risk to spur investment. The government also plays an important role in disseminating information as to sustainable chemistry practices and products throughout the marketplace, including to companies and consumers.

In addition to the direct benefits of sustainable chemistry, the use of sustainable chemistry products and processes by U.S. manufacturing companies can bolster the security and resilience of the national supply chains using circular and U.S. sources of feedstock materials, less frequent and shorter distance transport of hazardous materials, and improved safety. The expected outcome of Goal 3 is to enable American industries to use sustainable chemistry practices, allow consumers to make sustainable chemistry informed decisions, and manufacture sustainable products to remain resilient and globally competitive.

The tasks under each objective in Goal 3 are presented in relative order of the expected timeline for completion, without implying interdependency or prerequisites to execution. The initial tasks within an objective are more near-term tasks, and the latter tasks within an objective are long-term tasks.

Objective 3.1: Identify barriers for adoption and opportunities to encourage adoption of more sustainable alternatives to current market offerings.

Obtaining a comprehensive understanding of the barriers to adoption of more sustainable chemistries will highlight key issues that restrain growth. This information could be determined through literature reviews, surveys, and extended interviews with members of the public, as well as industrial and federal government subject matter experts. Consolidation of the known barriers into a centralized location could enable federal agencies to understand the needs of industries, markets, and communities (especially those with EJ concerns). In addition, this process can reveal stories of successful implementation where lessons may be gleaned and help prioritize key opportunities to maximize governmental efforts to support sustainable chemistry.

Task 3.1.1: Gather information on non-technical barriers regarding the implementation of sustainable chemistry products or processes.

Federal agencies need to have a sufficient understanding of the technical and non-technical barriers to implement sustainable chemistry products and processes. This information could allow the federal government to identify and prioritize sustainable chemistry solutions and research needs. A coordinated, federal approach may improve the outcomes of RFIs, individual sector listening sessions, and scientific workshops or symposia. This federal coordination effort could leverage previous stakeholder engagement efforts, workshops, and RFI results.

Task 3.1.2: Engage with industry stakeholders to identify barriers and solutions to implement sustainable chemistry products and processes that are specific to small and medium businesses.

The efforts of **Task 3.1.1** are focused on identifying common barriers for all manufacturers and other businesses to implement sustainable chemistry practices, but there may be barriers that are specific to small and medium enterprises that should be addressed in addition to the common barriers. Small and medium enterprises may bear a disproportionately greater burden to adopt sustainable chemistry, and related sustainable engineering and manufacturing principles, as compared to larger companies. Small and medium businesses are disproportionately affected by limited availability of sustainable chemistry expertise, employee bandwidth, commercially available sustainable feedstocks, and high start-up costs for adopting new, sustainable chemical processes. In addition to the efforts of **Task 3.1.1**, stakeholder outreach efforts by federal agencies should engage, specifically, with small and medium enterprises.

> ***Crosscutting Theme: Business Engagement with Small and Medium Enterprises***
> Stakeholder engagement with small and medium enterprises, through targeted workshops, seminars, and sector-specific meetings, will be critical for federal agencies to comprehensively identify the barriers that these businesses face and to collaboratively generate solutions for the implementation of sustainable chemistry products and processes that keep environmental justice principles at the forefront of these decisions.

Task 3.1.3: Connect manufacturers and other businesses that produce sustainable chemical products to industries that are looking for solutions for their current, less sustainable products or processes.

Federal agencies could host events or resources that connect manufacturers and researchers producing sustainable chemistry solutions to those companies faced with specific issues, such as cultural or economic barriers, to the adoption of new and more sustainable products or processes. These actions can include connecting communities that are impacted by less sustainable supply chains to manufacturers of more sustainable solutions to alleviate to burden of unsustainable chemistries on communities burdened by environmental injustices. These fora could include development of consortia to take place in the pre-competitive space where advances could help support companies of varying size. The federal government may also coordinate collaborative events with industry/producers and underrepresented community members to identify and highlight the array of barriers and the solutions that could satisfy multiple and complex needs. For example, USDA's BioPreferred Program connects manufacturers of sustainable ingredients or products with industries that are looking for sustainable alternatives.

Task 3.1.4: Coordinate with non-federal governmental organizations at the state, local, Tribal, and territorial levels, to identify opportunities to support more sustainable chemistry alternatives.

Regulatory and non-regulatory efforts at the non-federal level could provide a greater impact by addressing relevant needs of communities impacted by harmful chemical pollution. Close engagement with state, local, and tribal governments and burdened communities, through listening sessions, educational workshops, and other options for cross-governmental dialogue, would help federal agencies understand the communities' respective needs, while also helping to identify opportunities to advocate for, and adopt, more sustainable practices and policies.

Objective 3.2: Incorporate sustainability into the national security assessments of products.

Policies that impact access to chemicals have implications for U.S. national and economic security, given the importance of chemicals to U.S. industrial, public health, food, textile, and agricultural ecosystems. Chemicals are a potential risk factor in supply chains. The potential causes of the risks vary from capture of products by non-market actors, logistical disruptions due to climate and conflict, to resource scarcity to pollution. The Department of Homeland Security further cites chemicals as one of 16 critical infrastructure sectors.[30] Sustainable chemistry offers a potential means of risk mitigation, and can reduce dependencies, while enabling access in a manner that benefits all Americans and the global community. This diversification of chemical and alternatives technologies will make supply chains more resilient, while enhancing U.S. technological leadership and economic competitiveness.

[30] Cybersecurity & Infrastructure Security Agency, "Critical Infrastructure Sectors." https://www.cisa.gov/topics/critical-infrastructure-security-and-resilience/critical-infrastructure-sectors

Task 3.2.1: Support the inclusion of sustainable chemistry into U.S. federal manufacturing strategy, as well as U.S. supply chain studies.

Federal agencies could leverage current initiatives to incorporate sustainable chemistry metrics into federal strategy regarding U.S. manufacturing and supply chain studies. Examples include the Biden-Harris Administration priorities, such as EO 14017: America's Supply Chains[31] and EO 14081: Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy.[32] Special considerations may need to be made to address the disproportionate, unique burdens faced by small and medium chemical enterprises to allow them to be competitive in this market.

Task 3.2.2: Develop strategic partnerships with trade organizations and industrial groups to identify and understand specific risks and research needs regarding critical infrastructure sectors.

Public-private partnerships with trade organizations within critical infrastructure sectors could enable federal agencies to identify and understand industry needs. There are multiple models implemented across the federal agencies to address industry challenges.

Federal Efforts in Sustainable Chemistry

An example of strategic partnerships include those established as part of the CHIPS for America Act. As part of the CHIPS for America investment, a digital twin manufacturing institute has recently been awarded, and NIST is partnering with the Semiconductor Research Corporation, via SemiSynBio, to develop biological computing systems. Other examples of strategic partnerships is the establishment of the NSTC Workforce Center of Excellence. The CHIPS and Science Act also supports accelerating materials innovation for sustainable semiconductors (CARISSMA) and PFAS abatement in semiconductor manufacturing (PRISM).

Objective 3.3: Implement standardized data infrastructure to support a sustainable supply chain.

One key area highlighted in the 2023 SC Landscape Report, and presented in Goal 1 of this strategic plan, is the importance of making an entire manufacturing process more sustainable, and not just individual steps in that process. Data infrastructures can support the validation and security of sustainable supply chain claims and transactions. These resources provide the paths, tools, and methods to create, manage, and secure data for organizations relying on data sharing across existing digital infrastructures. Without a dependable data infrastructure, the positioning, navigating, and timing of sustainable chemistry resources pose risks to critical sectors, potentially creating disruptions in supply chains and services. Supply chain security and resilience mutually benefit all stakeholders, fostering economic growth through competition and innovation. Targeting investments in open-access

[31] Executive Order 14017 on February 24, 2021, "America's Supply Chains." https://www.federalregister.gov/documents/2021/03/01/2021-04280/americas-supply-chains

[32] Executive Order 14081 on April 27, 2023, "Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy." https://www.federalregister.gov/documents/2023/04/27/2023-08841/executive-order-14081-advancing-biotechnology-and-biomanufacturing-innovation-for-a-sustainable-safe

data infrastructures for sustainable chemistry can generate opportunities, spur innovation, and strengthen productivity in sectors currently siloed by barriers.

Task 3.3.1: Through collaboration with industry stakeholders, develop recommendations to improve interoperability among reporting and certification standards for sustainable chemistry metrics.

Strengthening coordination and collaboration amongst U.S. agencies and the private sector will better enable coordinated anticipation of and leadership in reporting standards for sustainable chemistry metrics. Stakeholder collaboration could occur through Public-Private Partnership Entities on Sustainable Chemistry presented above. Electronic shipping papers are frequently required when chemicals and materials are transported. Currently, the shipping papers require minimum data reporting, standard reporting formats, and could potentially include sustainability information in the future.

Federal Efforts in Sustainable Chemistry

In May 2024, the Securities and Exchange Commission (SEC) released final rules on The Enhancement and Standardization of Climate-Related Disclosures for Investors, which is intended to provide "consistent, comparable, and decision-useful information" regarding climate risk within a company's SEC filings. This standardization for reporting climate-related disclosures could be adapted for reporting other sustainability concepts.

Task 3.3.2: Establish tools that enable customers to digitally assess sustainability information and credibility of sustainable chemistry claims in transactions.

Agencies could coordinate to develop a federal program for the establishment of digital passport and/or digital twin processes that enable digital representation of sustainable chemistry products, and provide traceable information regarding the sustainable chemistry metrics. Information such as life cycle assessments of products and supply chain analyses could be incorporated into the sustainable chemistry framework to develop accurate sustainability metrics and to communicate the impact of a chemical product or process. For example, the USDA BioPreferred Program[33] catalog data could be used to support tools to assist consumers in evaluating sustainability information and credibility of sustainability claims.

Task 3.3.3: Support public and private recognition of international sustainable chemistry specifications and standards.

International trade and investment dialogues could include commitments to collaborate on the development of sustainable chemistry technologies and services, including the ecosystem of data infrastructure, policies, and investments that will be needed to achieve scale. These agreements could seek to build the pathways for U.S. companies that emphasize sustainable chemistry to enter new international markets, such as commitments to support and to develop

[33] U.S. Department of Agriculture, "BioPreferred." https://www.biopreferred.gov/BioPreferred/.

international standards and specifications. By agreeing on mutually recognized specifications, voluntary international standards and certifications for design, expanded labeling and recycling programs could be developed in alignment with, and acceptance of, public values. This includes the hard work of operationalizing translation and interoperability in the international network of specifications and standards and leveraging U.S. supply chain, sustainable chemicals analyses, and programs to identify opportunities to advance the U.S. sustainable chemistry strategy.

Objective 3.4: Enable a sustainable chemistry-literate workforce through education and training.

The successful implementation of sustainable chemistry practices into current manufacturing processes will require a workforce that has been sufficiently trained in the new processes and products. Continued incorporation of sustainable chemistry into STEM education is important, but training (or re-training) the current workforce to enable sustainable chemistry-focused thinking and practices will be critical to industries and communities modifying their products and processes to more sustainable alternatives. This sustainable chemistry workforce training could address the capabilities and needs of the existing workforce, while being accessible to a wide range of educational and training backgrounds.

Task 3.4.1: Identify industries, occupations, skills, and credentials needed in sustainable chemistry manufacturing through federal engagement with industry and trade organizations.

To provide training guidelines for a sustainable chemistry-literate workforce, federal agencies should engage with industry, trade organizations, professional societies, researchers, and workers to characterize the training needs of the workforce. In addition, coordination between the federal agencies and these groups could identify new sustainable chemistry processes and products that may require workforce training.

Task 3.4.2: Develop informational documents, training modules, and/or guidance that enable industry and trade organizations to create curricula for sustainable chemistry workforce transitions in specific market sectors, including workforce safety training.

Through coordination with industries and professional societies, federal agencies can support the development of sustainable chemistry training guidance and tools, improve access to sustainable chemistry workforce training for businesses of all sizes, and incorporate sustainability into federal workforce safety programs. Federal programs like the NIEHS Environmental Career Worker Training Program could be developed to teach new skills to existing workforces with regards to sustainable chemistry. [34]

[34] National Institute of Environmental Health Sciences, "Environmental Career Worker Training Program." https://www.niehs.nih.gov/careers/hazmat/training_program_areas/ecwtp.

Crosscutting Theme: Circularity and Workforce Sustainability Training
Federal agencies will play an important role in training the current and future workforce for Sustainable Chemistry. For example, the National Institute of Standards and Technology (NIST) has developed the Training for Improving Plastics Circularity that includes workforce training modules, such as short courses and certification programs. NSF's INTERN program provides graduate students with experiential learning opportunities through research internships in non-academic settings so they can acquire core professional competencies and skills complementary to traditional academic training in preparation for multiple career pathways in any sector of the U.S. economy. Such concepts could also be applied to workforce training in areas such as green solvents and safe chemical handling.

Task 3.4.3: Support the incorporation of sustainable chemistry into higher STEM education via grants and support for internships.

Developing and incorporating sustainable chemistry principles and practices into STEM curricula could increase awareness and acceptance for the future workforce. Learning about sustainable chemistry principles and practices could help the next generation more easily incorporate sustainability into their future careers. Promoting interdisciplinary undergraduate and graduate programs and degrees in science, technology, and engineering would benefit from multidisciplinary curricula in sustainable chemistry topics. These curricula can include process design, circular economy, life cycle or technoeconomic assessment, toxicological risk assessment as applied to chemistry and chemical technologies, and the regulatory environment regarding sustainable chemistry. Such educational efforts may require funding mechanisms that encourage bridging different college units across campus.

Task 3.4.4: Enhance information sharing and dialog to foster a broad foundation for sustainable chemistry.

The federal government has a role in promoting sustainable chemistry education and information exchange. A dialog that provides information on sustainable chemistry advancements and supports the exchange of information could build trust and inform future choices that are consistent with sustainable chemistry processes and products. These efforts could encourage early adoption of sustainable chemistry solutions.

Objective 3.5: Enable sustainable chemistry supply chains by advancing innovative transportation systems.

Sustainable chemistry is inaccessible without a safe, efficient, and resilient means to distribute and transfer goods. Transportation can be a significant factor in the overall sustainability of a process or product. Efforts are ongoing within the U.S. Department of Transportation (US DOT) to repair and modernize highways, bridges, ports, waterways, airports, rail facilities, and other transit assets and facilities. These efforts aim to increase competitiveness and access to sustainable chemistry products and processes, driving down the cost of goods, reducing air pollution and greenhouse gas emissions, and reducing exposure to hazardous materials, waste, emissions, and other harmful outcomes. Implementation of the Infrastructure Investment and Jobs Act, a once-in-a-generation investment to create a transportation system that works for every American, is road mapped in the US DOT 2022-2026 Strategic Plan.[35, 36] Rapid acceleration of a decarbonized transportation fleet (boats, rail, and trucks with decreased greenhouse gas emissions) is also a factor in sustainability of chemicals and materials supply chains. As transportation infrastructure is renewed, the products of deconstruction and demolition projects need better pathways back into the supply chain. Additionally, solutions that minimize the demand for physical transportation and associated energy costs can be implemented, such as co-locating facilities and distributed manufacturing along supply chains.

Task 3.5.1: Restore and modernize core transportation assets to improve the state of repair, enhance resiliency, and expand beneficial new projects.

Federal agencies could serve as an example of how businesses, local governments, and other stakeholders that could help advance sustainable chemistry through transportation. This could include strengthening asset management systems and practices to reduce the costs of managing transportation assets, such as a fleet of vehicles. Repair and development of critical U.S. transportation infrastructure could be addressed in part through the assessment of freight and supply chain trends and technologies, the evaluation of critical supply chain vulnerabilities that affect economic security and resiliency, and the convening of supply chain stakeholders across freight sectors to reach commitments to support safer and more resilient supply chains. The data, tools, and outcomes from these federal efforts could provide insights that are valuable for businesses and local communities to restore and/or modernize their transportations assets.

Task 3.5.2: Incorporate the sustainability of transportation into sustainable chemistry framework.

The sustainability of manufactured products should consider impact and consequences of the transportation systems involved in moving materials and delivering the final products to consumers, as they relate to the attributes of the sustainable chemistry definition. Significant advances in the transportation sector are ongoing through use of electrification, batteries, and clean hydrogen to support transportation equipment, but implementation needs to be further accelerated. In addition, there are some transportation approaches, such as long-distance shipping and aviation, where significant progress is still needed for them to be performed using sustainable energy sources at a competitive cost.

[35] The White House, “Fact Sheet: The Bipartisan Infrastructure Deal.” November 2023. https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/.

[36] U.S. Department of Transportation, “U.S. DOT Strategic Plan FY 2022-2026.” https://www.transportation.gov/mission/us-dot-strategic-plan-fy-2022-2026.

Task 3.5.3: Incorporate more sustainable system operations to minimize travel demand, increase travel reliability, and improve safety and connectivity.

To promote the adoption of noteworthy multimodal transportation systems management and operations practices, improved incident and emergency response and recovery practices are needed to reduce system disruption. Partnerships are also needed to manage disruptions to system operations safely and effectively and optimize system performance for all system users. Investments in multimodal capacity could improve travel time reliability on congested corridors. Examples of more sustainable approaches could include transportation infrastructure that incorporates sustainable materials such as lower climate impact concrete, as well as continued advances in materials reuse. Other improvements including colocation technologies and distributed manufacturing are examples of vertical integration and could be coupled with sustainable chemistry advances as a way to reduce emissions, time, and cost.

Goal 4: Creating a 21st Century Federal Service for Sustainable Chemistry

As part of the strategy to elevate sustainable chemistry products and processes, federal agencies could integrate sustainable chemistry principles and practices into their policies and procedures. As originally described in the 2023 SC Landscape Report, the federal government has many roles in sustainable chemistry, as a regulator, as a large purchaser of goods and services, and as a market facilitator through the gathering and disseminating of information. In addition, the federal government can incorporate expertise on emerging areas of sustainable chemistry through education, R&D, and strategic recruitment of subject matter expertise. This goal focuses inward on the operations of federal agencies and opportunities to strengthen public service in advancing sustainable chemistry. Many of the objectives identified are complementary to challenges and opportunities called out elsewhere, such as the National Emerging Contaminants Research Initiative[37], bioeconomy[38], and federal research regarding per- and polyfluoroalkyl substances.[39] Industrial decarbonization can be an important aspect of sustainable chemistry by presenting an opportunity to not only reduce carbon emissions but also implement chemicals manufacturing processes that are less hazardous. Policies that enable federal agencies to adopt sustainable chemistry principles and practices include the lowering of barriers to share data and knowledge regarding sustainable chemistry, developing federal workforce in sustainable chemistry, establishing working groups and other groups of subject matter experts to identify priorities and opportunities in sustainable chemistry, and actively engaging with private organizations to make sure priorities and opportunities align with the private sector. The expected

[37] National Science and Technology Council, Contaminants of Emerging Concern Strategy Team, "National Emerging Contaminants Research Initiative," August 2022. https://www.whitehouse.gov/wp-content/uploads/2022/08/08-2022-National-Emerging-Contaminants-Research-Initiative.pdf

[38] National Science and Technology Council, Interagency Working Group on Data for the Bioeconomy, "Vision, Needs, and Proposed Actions for Data for the Bioeconomy Initiative," December 2023. https://www.whitehouse.gov/wp-content/uploads/2023/12/FINAL-Data-for-the-Bioeconomy-Initiative-Report.pdf

[39] National Science and Technology Council, Per- and Polyfluoroalkyl Substances Strategy Team, "Per- and Polyfluoroalkyl Substances (PFAS) Report," March 2023. https://www.whitehouse.gov/wp-content/uploads/2023/03/OSTP-March-2023-PFAS-Report.pdf

outcome of Goal 4 is to create a federal government that fully embraces sustainable chemistry in every aspect of its operations.

The federal government activities will be important for different aspects in the development of sustainable chemistry processes. These activities include not only the training of current and future workforce in sustainability, but also building federal expertise in sustainable chemistry. Such efforts could leverage public-private partnerships, take advantage of existing federal workforce development programs, and identify innovative ways to educate and attract the next generation of federal sustainable chemistry leaders.

Objective 4.1: Acquire new federal workforce expertise in more sustainable chemistries.

Many challenges face the federal workforce today, including maintaining the knowledge base and skills necessary for informed decision making in a complex and evolving world. For example, emerging areas —ranging from systems science to data science, including AI methods, to community resilience—are rapidly developing and often extend beyond traditional domain science. This federal workforce effort could complement, and leverage, the broader workforce efforts presented in **Objective 3.4**. Sustainable chemistry topics require broader knowledge across a range of fields where adequate training mechanisms do not exist. Public-private partnerships created in response to this strategic plan could bring together federal agencies to work collaboratively with industry, academia, and NGOs to identify advances in science or technology in sustainable chemistry. Continuing education and connection of federal employees with relevant stakeholders could enable a workforce to more effectively respond to the challenges in sustainable chemistry today and in the future.

Beyond additional training of the existing workforce, it is important to recognize the challenges facing new hiring in scientific/engineering fields in the federal government. It can be challenging to attract top talent to public service rather than the private sector, especially in emerging areas such as SC and AI. Additionally, enthusiasm for the area of sustainable chemistry science and technologies may be tempered by lack of awareness of opportunities in government for effective use of their broad training and expertise.

Task 4.1.1: Develop comprehensive sustainable chemistry training and education programs across the federal government.

Agencies could consider developing comprehensive programs akin to, or within, the Presidential Innovation Fellows program or through Pathways Programs across the federal complex for better education and dissemination of the roles each agency plays in the sustainable chemistry landscape.[40,41] This effort could create a more connected and informed ecosystem across government. Similarly, programs could be developed for federal employees to engage with industry and NGOs in the sustainable chemistry sector. A Federal Sustainability

[40] U.S. General Services Administration, "Presidential Innovation Fellows." https://presidentialinnovationfellows.gov/.

[41] U.S. Office of Personnel Management, "Pathways Programs Final Rule Overview | Students & Recent Graduates." https://www.opm.gov/policy-data-oversight/hiring-information/students-recent-graduates/.

Institute, akin to the Federal Executive Institute,[42] would allow for training federal core staff and provide knowledge through guest or visiting lecturers from public and private organizations.

Task 4.1.2: Develop a federal workforce development hiring strategy.

Agencies could establish hiring clearinghouses in sustainable chemistry for the specialized expertise needed to address key challenges and opportunities. This should include development of specific, measurable, actionable, and time bound goals to develop a science, technology, engineering, and mathematics trained workforce which supports the advancement of EJ in the context of sustainable chemistry consistent with Administration priorities laid out in other documents.[43,44,45,46,47]

When appropriate, federal agencies could support apprenticeship and non-college skilled worker recruitment to reflect principles of inclusive economic growth and workforce development as championed by White House initiatives.[48]

Ambitious cross-government, public relations campaigns (social media, podcasts, etc.) and outreach (professional society events) could detail the critical need for a vibrant federal workforce in sustainable chemistry and the value/impact of public service on the nation.

Objective 4.2: Elevate recognition of success in sustainable chemistry.

Success within the strategic goals can be recognized through various platforms such as awards and grants. Several agencies have awards and other mechanisms for recognizing success in many sectors. By incorporating sustainable chemistry principles into the evaluation of award recipients, and by directly rewarding new achievements in sustainable chemistry, agencies can further elevate sustainable chemistry. These successes can signal and accelerate a move towards creating a 21st century federal service for sustainable chemistry.

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[42] U.S. Office of Personnel Management, "Federal Executive Institute." https://www.opm.gov/services-for-agencies/center-for-leadership-development/federal-executive-institute/.

[43] Office of Science and Technology Policy. National Science and Technology Council, Environmental Justice Subcommittee. Environmental Justice Science, Data, and Research Plan. July 2024. https://www.whitehouse.gov/wp-content/uploads/2024/07/NSTC-EJ-Research-Plan-July-2024.pdf.

[44] Office of Management and Budget. Study to Identify Methods to Assess Equity: Report to the President. Executive Office of the President, 20 July 2021, https://www.whitehouse.gov/wp-content/uploads/2021/08/OMB-Report-on-E013985-Implementation_508-Compliant-Secure-v1.1.pdf.

[45] Office of Science and Technology Policy, National Science and Technology Council, Subcommittee on Equitable Data. A Vision for Equitable Data Recommendations From the Equitable Data Working Group. Executive Office of the President. www.whitehouse.gov/wp-content/uploads/2022/04/eo13985-vision-for-equitable-data.pdf.

[46] U.S. Government Accountability Office. Science and Technology: Strengthening and Sustaining the Federal Science and Technology Workforce. GAO-21-461T, 17 March 2021, https://www.gao.gov/assets/gao-21-461t.pdf.

[47] U.S. Office of Personnel Management. Agency Equity Action Plan - Strategies to Advance Equity in FY 2024. https://www.opm.gov/about-us/agency-equity-action-plan/strategies-to-advance-equity-in-fy-2024/.

[48] "Remarks by Vice President Harris on Expanding Registered Apprenticeship Programs, Creating Good-Paying Union Jobs, and Advancing Economic Opportunity | Madison, MI," March 6, 2024. https://www.whitehouse.gov/briefing-room/speeches-remarks/2024/03/06/remarks-by-vice-president-harris-on-expanding-registered-apprenticeship-programs-creating-good-paying-union-jobs-and-advancing-economic-opportunity-madison-mi/.

Task 4.2.1: Elevate agency success in sustainable chemistry.

Success of emerging research projects in sustainable chemistry, including fundamental knowledge, novel technologies resulting from these fundamental science advancements, and applications, could be highlighted by federal agencies. Beyond the typical tools routinely used, agencies can engage more directly in symposium, conference, and workshop organization, incorporating career fairs that feature federal researchers and lower barriers to promoting agency missions and accomplishments to the public.

Task 4.2.2: Utilize the Public Service Award program, and other awards or prizes to incentivize and recognize Sustainable Chemistry Advancements.

The Public Service Award program[49] was created to incentivize the Manufacturing USA Institutes to take on pandemic-related work during the SARS-CoV-2 pandemic. These awards are intended to support high-impact public service projects regarding manufacturing. The program could extend or expand on the awards to create sustainable chemistry dedicated workflows in existing manufacturing institutes' technology focus areas.[50] Other public programs, awards, and prizes could be similarly modified or extended to explicitly recognize sustainable chemistry advancements at the federal level.

Objective 4.3: Lower barriers to interagency cooperation on sustainable chemistry.

Effective communication and collaboration across relevant federal agencies will be central to advancing sustainable chemistry for the benefit of the nation and more broadly the world. Federal agencies can engage in interagency activities such as research solicitations; however, logistics can be a challenge because the timing, available support, and funding mechanisms may differ across agencies. While agencies share information informally with each other, more formal mechanisms of communication could be established to ensure effective collaboration and increase impact. Feedback loops could be established to enable federal agency communication about sustainable chemistry advancements, as well as factoring in community input about the opportunities, challenges, and concerns for sustainable chemistry.

Task 4.3.1: Design and establish a new federal entity for sustainable chemistry processes.

A new federally managed national entity, such as an institute, laboratory, or research center, could be established to advance sustainable chemistry among multiple federal agencies. This entity could be supported and governed by multiple federal agencies and be dedicated to pilot-scale technology development for sustainable chemistry processes. It could also include a modern chemistry testbed and training capacity for developing more sustainable chemical products and processes. In addition, the proposed entity could champion stakeholder and public engagement and education activities, and could advance socio-economic research to

[49] Two examples of Public Service Awards, include NIST's WEAVE (https://www.nist.gov/oam/manufacturing-usa-workforce-education-and-vibrant-ecosystems-weave-public-service-awards) and RACER program (https://www.nist.gov/oam/rapid-assistance-coronavirus-economic-response-racer-grant-program).

[50] Examples of Public Service Awards are shown on the NIST OAM website: https://www.nist.gov/oam/funding-opportunities.

better model, predict and efficiently implement system-wide sustainable chemistry solutions. Goals could combine research, training, and engagement with diverse communities. The proposed effort should be complementary to existing efforts, and other facilities that focus on critical national priority research. The scope of this entity could be to support the sustainable chemistry challenges highlighted across this strategic plan. It is noted that the creation of a new federal entity would require a significant and sustained investment for the formation and maintenance of said infrastructure.

Task 4.3.2: Improve information, data, and process sharing among federal agencies.

Strategies and opportunities could be identified and developed where agencies can share information and data on awards, funding opportunities, agency timelines, opportunities for collaboration, and successes and roadblocks for sustainable chemistry. An example would be a centrally co-located, user-centric resource that would inform development of potential interagency collaborations, as well as keep all agency representatives up to date on what agencies are doing independently. Other examples of approaches for this effort are described in the National Emerging Contaminants Research Initiative Implementation Plan.[51]

Task 4.3.3: Identify and support interagency funding opportunities.

Federal interagency funding (co-funding of a project by more than one federal agency) can be a logistical challenge. However, the potential for interagency funding to support priority scientific and technical areas can foster multidisciplinary and multipurpose projects (e.g., fundamental scientific research and industry transitional research within the same project). Funding could support fundamental, transitional, or applied research, as well as workshops.

Objective 4.4: Establish innovative public-private partnerships dedicated to advancing sustainable chemistry.

From challenges to combat marine debris[52] to innovative impact absorbing materials[53] to better recirculation models or materials, the federal government has been exploring alternative methods of engaging with the private sector to accelerate transferrable and scalable solutions. A key opportunity for new models in this space is the combination of research, centralized data resource stewardship, and support for knowledge transfer between federal agencies and private stakeholders. Notably, direct partnerships between the public and private sectors can support effective outcomes of goals across the Sustainable Chemistry Strategic Plan.

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[51] National Science and Technology Council, Contaminants of Emerging Concern Strategy Team, "National Emerging Contaminants Research Initiative Implementation Plan," January 2024. https://www.whitehouse.gov/wp-content/uploads/2024/01/NSTC-CEC-Strategy-Team-NECRI-Implementation-Plan.pdf

[52] National Oceanographic and Atmospheric Administration, "Sea Grant announces funding opportunities to support community-engaged marine debris removal and prevention." https://seagrant.noaa.gov/sea-grant-announces-funding-opportunities-to-support-community-engaged-marine-debris-removal-and-prevention/.

[53] National Institute of Standards and Technology, "Head Health Challenge III." https://www.challenge.gov/toolkit/case-studies/head-health-challenge-iii/.

Task 4.4.1: Create new public-private partnership entities that are explicitly dedicated to sustainable chemistry.

In pursuit of the development of metrics and frameworks, federal agencies could evaluate the use of public-private partnerships, including understanding resource needs and information gaps. The new entities could focus on the elements of the definition of sustainable chemistry broadly and include ambitious, focused efforts on data and modeling (including CARE and FAIR principles, stewardship roles and access model innovation)[54], EJ, social challenges to widespread sustainable chemistry adoption, chemical process innovation and policy dialogue forums to support appropriate, targeted communication and information sharing between the public and private sectors.

Task 4.4.2: Establish grant and supplement programs for cooperative fellowships among academia, industry, and the federal government.

Federal grant/supplement programs could be established to support fellowships within the federal government and academia where private sector employees can seek deeper training and draw knowledge into industries more quickly and efficiently from time spent in academic and governmental research. Similarly, these programs could provide support for internships, postdoctoral researchers, and sabbatical funding for academic faculty to spend time in industry learning about practical, near-term challenges in need of solutions. The fellowships, funded by the appropriate federal agency or perhaps by an interagency opportunity, could help develop a productive feedback loop between sustainable chemistry researchers and industry looking to implement sustainable chemistry processes and products.

Objective 4.5: Leverage existing networks and tools to advance sustainable chemistry solutions.

Sustainable chemistry innovation should be an integrated element of many programs and activities across the federal government. Its application is critical across all chemical sectors; therefore, it could be explored through designated new efforts and take advantage of current efforts and tools already in place. This objective includes looking across the existing portfolio of investments (government research, cooperative agreements, contracts, grants) and using the power of cross-cutting investments (e.g., Manufacturing USA's Public Service funding awards), joint working groups, and other means of coordination to advance innovation in programs ranging from principal investigator grants to the Manufacturing Institutes.

Task 4.5.1: Format extramural programs to utilize supplemental grants to support shifting or adapting funded research to incorporate sustainable chemistry innovation.

Like supplemental grants to support collaboration and utilization of specific scientific resources, such as the NIST Center for Neutron Research, extramural programs could utilize

[54] Carroll *et al., (*April 16, 2021). "Operationalizing the CARE and FAIR Principles for Indigenous data futures." https://www.nature.com/articles/s41597-021-00892-0.

supplemental grants to enable funded researchers to shift or adapt their project goals towards sustainable chemistry-driven research and innovation. [55]

Task 4.5.2: Augment existing federal programs and initiatives to fund small and medium enterprise equipment, infrastructure, or workforce training.

Existing programs, such as NIST's Manufacturing Extension Program or infrastructure grant programs at DOE, NSF, and EPA, could provide small and medium enterprises with funding for equipment, infrastructure, or workforce training through supplements to an existing award or additional funding calls targeted for this purpose. Similarly, other major investments, such as Bipartisan Infrastructure Law, Inflation Reduction Act, and the CHIPS and Science Act, may be leveraged to include opportunities to incorporate sustainable chemistry in their implementation.

Conclusion

Successful implementation of this strategic plan will help to successfully address regulatory, scientific, mitigation gaps, disproportionate exposure to unsustainable chemistries, and strengthen and advance the state of the science. While outside the scope of this report, the SC ST recognizes there are additional research needs that should be further explored through intramural and extramural research, including deep and sustained courses of work between stakeholders to achieve an implementation plan for sustainable chemistry evaluation metrics and assessments, as well as the impacts of advancing sustainable chemistry on communities striving for EJ. The NDAA for FY2021 requires the SC ST to report to Congress on the status of the strategic plan every three years (through December 31, 2030), including a summary of federally funded sustainable chemistry research, development, demonstration, technology transfer, commercialization, education, and training activities; a summary of the financial resources allocated to sustainable chemistry initiatives by each participating agency; an analysis of the progress made toward achieving the goals and priorities of this subtitle, and recommendations for future program activities; and an evaluation of steps taken and future strategies to avoid duplication of efforts, streamline interagency coordination, facilitate information sharing, and spread best practices among participating agencies; and an evaluation of duplicative federal funding and duplicative federal research in sustainable chemistry, efforts undertaken by the entity to eliminate duplicative funding and research, and recommendations on how to achieve these goals. [56]

The breadth and complexity of transitioning chemical industries and the reliant economies/sectors to more sustainable chemistry practices will take large-scale efforts across government, industries, academia, and the public. Extending the work of the SC ST beyond the defined NDAA timeline is integral

[55] National Institute of Standards & Technology, "NIST Center for Neutron Research." https://www.nist.gov/ncnr

[56] William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021. H.R. 6395, 116th Cong. (2021). https://www.congress.gov/bill/116th-congress/house-bill/6395.

to the implementation of the strategic plan, as addressing these challenges will extend well beyond 2030.

Dedicated public and private resources will be critical to advancing sustainable chemistry solutions, and collaboration is recommended to empower the success of these efforts. The SC ST will continue to support interagency coordination during the implementation of the strategic plan and engage with external stakeholders to adopt more sustainable chemistry solutions as the understanding of what sustainability means continues to evolve.

Appendix A: Intersection of strategic objectives and crosscutting themes

To further illustrate the intersection of the crosscutting themes and the strategic objectives, the figure below shows the layout of the strategic plan and crosscutting themes.

		Crosscutting themes				
		Federal Investment	Circular Economy	Data Sharing and Artificial Intelligence (AI)	Environmental Justice and Equity	Education/Community Engagement
Goal 1: Discovering More Sustainable Chemistry for Future Solutions						
1.1	Establish a systems thinking approach for the development sustainable chemistry products and processes					
1.2	Develop and utilize alternative sustainable energy sources to drive chemical processes.					
1.3	Identify and incorporate sustainable starting materials into chemical processes.					
1.4	Develop sustainable approaches to address unit operations in chemical processes.					
1.5	Develop innovative chemical transformations to drive sustainable chemistry solutions.					
1.6	Leverage data-driven approaches to advance sustainable chemistry practices.					
Goal 2 : Supporting, Building, and Bridging Sustainable Chemistry from Discovery to Commercialization						
2.1	Motivate the chemical sector to converge towards key technical challenges of scaling up sustainable chemistry solutions.					
2.2	Support the development and adoption of comprehensive decision models, metrics, and data management systems to evaluate sustainable chemistry processes and products.					
2.3	Facilitate and accelerate the sustainable chemistry transition from discovery to implementation.					
Goal 3: Promoting Adoption and Growth of Sustainable Chemistry in Businesses and Subnational Government						
3.1	Identify barriers for adoption and opportunities to encourage adoption of more sustainable alternatives to current market offerings.					
3.2	Incorporate sustainability into the national security assessments of products.					
3.3	Implement standardized data infrastructure to support a sustainable supply chain.					
3.4	Enable a sustainable chemistry-literate workforce through education and training.					
3.5	Enable sustainable chemistry supply chains by advancing innovative transportation systems.					
Goal 4: Creating a 21st Century Federal Service for Sustainable Chemistry						
4.1	Acquire new federal workforce expertise in more sustainable chemistries.					
4.2	Elevate recognition of success in sustainable chemistry.					
4.3	Lower barriers to interagency cooperation on sustainable chemistry.					
4.4	Establish innovative public-private partnerships dedicated to advancing sustainable chemistry.					
4.5	Leverage existing networks and tools to advance sustainable chemistry solutions.					

Appendix B: Federal opportunities for the development of data sharing tools

Material quantity, composition, and energy needs are crucial for chemical life cycle analysis. Such data provide insights into the environmental impacts of chemical products across their manufacturing, use, and end-of-life stages. Therefore, comprehensive data on chemical-centric resource needs, environmental releases, and energy usage are important for performing objective evaluations and informing sustainable chemistry decision-making. Accessing and sharing high-quality, transparent, and standardized data can ensure the credibility and reliability of sustainable chemistry advancements. Data sharing facilitates comparisons and could steer improvements toward more sustainable chemicals and chemical life cycles. Also, data sharing assists stakeholders in identifying improvement opportunities, optimizing chemistry, enhancing chemical process designs, and formulating methods for eliminating and reducing environmental, health, energy, economic, and social burdens throughout a chemical's life cycle.

However, limited chemical data when manufacturing, using, and disposing chemicals can hamper the assessment of the environmental and human health impacts of chemical hazards. Thus, a federal effort to develop data-sharing tools could advance sustainable chemistry development. This could enable collaboration and transparency, accelerate the discovery and adoption of sustainable technologies, processes, and chemical products while protecting sensitive data. These advancements could leverage open science policies of federal agencies.

Opportunities for federal data sharing include, but are not limited to:

- Development of data platforms that enable the exchange of scientific achievement, chemical-centric human and environmental toxicology, resource needs, environmental releases, energy usage data, and best techniques among industry, government, and academic stakeholders.
- Facilitation of open access to standardized data and data sharing knowledge to overcome challenges, optimize processes, develop innovative solutions that minimize environmental and health impacts, and optimize resource and energy efficiency.
- Promote transparent chemical-centric sustainability data reporting to drive the transition toward sustainable chemistry. This type of reporting could facilitate the tracking of chemical transfers and environmental releases across the manufacturing, use, and end-of-life stages.
- Development of standardized database storage and data sharing systems and procedures to collect, upload, manage, and convert raw data from different siloed database systems into usable information for data-driven models. These models could be used to describe and quickly evaluate a chemical and its life stages in terms of environmental and health risks, resource needs, environmental releases, energy usage, and circularity.