November 2026

FOCUS SHEET

Green and Sustainable Chemistry: Concepts, Approaches, and Applications



Prepared By

The Interstate Technology & Regulatory Council (ITRC)

Green & Sustainable Chemistry Team

EXECUTIVE SUMMARY

This Focus Sheet provides an introductory overview of green chemistry and sustainable chemistry concepts, selected assessment and design approaches, applications across the product life cycle, and factors that may affect implementation. It also presents selected federal and state programs and includes case studies and examples describing how particular concepts have been applied. The case studies and examples are illustrative and do not constitute ITRC endorsement of a company, product, technology, program, policy, or approach.

The Focus Sheet was informed in part by Environmental Council of the States (ECOS) Resolution 17-1, Advancing Safer Chemical Products and Processes, which expresses ECOS's position concerning green and sustainable chemistry and alternatives assessment (ECOS 2026). This document does not adopt the resolution as ITRC policy or prescribe how it should be implemented. Rather, it provides technical information that may help state environmental agencies and other interested parties understand relevant concepts, approaches, programs, applications, limitations, and potential tradeoffs.

The Focus Sheet is intended for:

- State and local government policy and decision makers seeking technical context for regulations, programs, procurement, incentives, or other government activities.
- Regulators, environmental professionals, technical assistance providers, educators, and students seeking to understand the concepts, approaches, applications, and implementation considerations presented in this document.
- Industry professionals, manufacturers, product designers, suppliers, and purchasers seeking information that may inform chemical, material, product, process, or procurement decisions.
- Researchers, nonprofit organizations, and other interested parties seeking a common foundation for evaluating green chemistry and sustainable chemistry information and selected examples.

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1 GREEN CHEMISTRY AND SUSTAINABLE CHEMISTRY

1.1 Green Chemistry

Green chemistry is a science-based approach for designing chemical products and processes that reduce or eliminate the use or generation of hazardous substances. The U.S. Environmental Protection Agency (USEPA) defines green chemistry as "the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal" (USEPA 2026b). The **12 principles of green chemistry** provide a framework for chemists, engineers, and manufacturers to consider when designing chemical products and processes (Anastas and Warner 1998).

1.2 Sustainable Chemistry

Sustainable chemistry encompasses the design, manufacture, use, and end-of-life management of chemicals, materials and products. A federal interagency definition describes sustainable chemistry, in part, as 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" (NSTC 2024). The broader definition also addresses human health and environmental impacts, circularity, societal needs, economic resilience, resource depletion, and waste accumulation. Sustainable chemistry therefore considers a range of environmental, economic, resource, and societal factors across the life cycle of chemicals, materials, and products.

1.3 Relationship Between Green Chemistry and Sustainable Chemistry

The terms *green chemistry* and *sustainable chemistry* are closely related and are sometimes used interchangeably, but they do not always describe the same scope of considerations. Green chemistry generally focuses on the intentional design of chemical products and processes to reduce or eliminate the use or generation of hazardous substances. Sustainable chemistry generally considers a broader set of factors associated with chemicals, materials, products, and processes. In addition to reducing hazards to human health and the environment, sustainable chemistry may consider resource and energy use, renewable feedstocks, circularity, economic viability and resilience, societal needs, and impacts throughout the product life cycle (NSTC 2024; UNEP 2021).

Although the two concepts overlap substantially, definitions and usage of green chemistry and sustainable chemistry vary among organizations and frameworks. The following definitions are used in this Focus Sheet:

- **Green chemistry** refers primarily to designing chemical products and processes that reduce or eliminate the use or generation of hazardous substances.
- **Sustainable chemistry** refers to the broader consideration of environmental, resource, life-cycle, economic, and societal factors.

The combined term *green and sustainable chemistry* (GSC) is used when the discussion applies to both concepts or to the broader collection of approaches represented by them. Use of the term GSC does not indicate that every green chemistry practice necessarily satisfies every sustainable chemistry consideration.

Green chemistry principles and practices can contribute to broader sustainability objectives, but a chemical product or process that performs well against one green chemistry attribute does not necessarily satisfy all relevant sustainability considerations. For example, alternatives may reduce the use of a hazardous substance while presenting tradeoffs related to energy consumption, resource availability, life-cycle impacts, cost, performance, or other environmental and societal factors. Evaluating sustainability may therefore require consideration of multiple attributes and potential tradeoffs rather than reliance on a single characteristic (NSTC 2024; UNEP 2021).

1.4 Why Consider Green and Sustainable Chemistry

GSC provides a framework for considering human-health, environmental, performance, economic, and resource factors during the design and selection of chemicals, materials, products, and processes. Applying GSC principles early in design and decision-making may help prevent pollution, reduce the use or generation of hazardous substances, use energy and materials more efficiently, and identify alternatives that meet functional and performance requirements. GSC may also support innovation and the development of products and processes that respond to changing market, supply-chain, and regulatory conditions (ECOS 2026; Golden et al. 2021).

Potential benefits and related considerations associated with GSC include the following:

- **Reducing chemical hazards and potential exposures.** GSC may involve replacing a chemical of concern with a less hazardous alternative, modifying a process to reduce hazardous inputs or byproducts, or redesigning a product or function so that the chemical is no longer needed. Considering hazard, exposure potential, performance, technical feasibility, and other relevant attributes may help reduce potential impacts on workers, consumers, communities, and ecosystems while reducing the likelihood of substitutions that shift hazards or impacts elsewhere (ECOS 2026; OECD 2021; USEPA 2026b).
- **Preventing pollution and reducing resource and waste-management demands.** Designing products and processes to prevent pollution at its source may reduce the generation of hazardous substances and wastes requiring treatment, management, or disposal (USEPA 2025a, 2026b). Depending on the application, GSC approaches may also reduce the use of energy, water, raw materials, and other resources throughout a product's life cycle (NSTC 2024; UNEP 2021). These changes may lessen associated material, waste-management, compliance, or remediation demands, although the results depend on the specific product, process, application, and decision context.
- **Supporting innovation and economic considerations.** GSC may encourage the development of products and processes that combine hazard reduction with functional performance, resource efficiency, and other design objectives. Potential benefits may include improved process efficiency, reduced material or waste-management costs, reduced exposure to certain future risks, and access to markets seeking products with improved health or environmental attributes (ECOS 2026; Golden et al. 2021). The extent of these benefits varies, and implementation may also involve research, development, testing, qualification, transition, and capital costs. GSC principles and alternatives assessment may support sustainable economic development, innovation, and high-value employment (ECOS 2026).
- **Supporting resource efficiency and material options.** Considering material availability, resource efficiency, feedstock options, and opportunities for reuse or circularity may help identify alternative ways to provide a required function while reducing reliance on particular materials or production pathways. Depending on the application, alternatives may differ in their availability, resource demands, scalability, performance, environmental impacts, and costs. These differences should be evaluated within the applicable decision context rather than assuming that

a renewable, recycled, or alternative feedstock is necessarily preferable (NSTC 2024; UNEP 2021).

The relevance of these potential benefits depends on the chemical, product, process, application, and decision context. An alternative that performs more favorably against one attribute may perform less favorably against another. For this reason, GSC should not be understood as a designation that a chemical or product is universally "green," "safe," or "sustainable." Rather, it provides principles and approaches for comparing options using relevant considerations such as hazard, exposure potential, performance, economic viability, and life-cycle impacts (ECOS 2026; OECD 2021; NSTC 2024; UNEP 2021).

GSC shifts attention upstream, from managing hazards and wastes after they are created toward preventing or reducing them through design and informed selection (ECOS 2026; USEPA 2026b). Broader adoption may require coordination among chemical manufacturers, product designers, purchasers, suppliers, regulators, researchers, and other participants across the value chain. Technical innovation is important, but implementation may also depend on access to information, performance requirements, costs, market demand, policy conditions, and appropriate incentives (Change Chemistry 2026; Golden et al. 2021).

1.5 Relationship to Circularity

Circularity, often discussed through the concept of "circular economy," seeks to retain the value of products, components, and materials while reducing waste and the consumption of resources. Circularity may involve maintaining, reusing, repairing, refurbishing, remanufacturing, or recycling products and materials. It may also include returning suitable biological materials safely to the environment through processes such as composting or anaerobic digestion (ECOS 2025). The USEPA similarly describes a circular economy as reducing material use, redesigning products and materials to be less resource intensive, and recapturing materials that might otherwise be considered waste (ECOS 2026; USEPA 2026h). The Ellen MacArthur Foundation describes the circular economy through three principles: eliminate waste and pollution, circulate products and materials at their highest value, and regenerate nature (Ellen MacArthur Foundation 2026).

Green chemistry, sustainable chemistry, and circularity are related but distinct concepts. GSC focuses on the attributes and impacts of chemicals, materials, products, and processes, while circularity focuses on how products and materials are designed, used, maintained, recovered, and circulated within biological or technical systems. Applying GSC principles does not necessarily make a product or system circular, and keeping a product or material in circulation does not necessarily make it less hazardous or more sustainable (OECD 2026a; UNEP 2021).

Chemical and material choices can affect whether and how products and materials may be safely and effectively maintained in circulation. For example, substances of concern, mixtures of incompatible materials, or additives that interfere with recovery processes may limit opportunities for reuse, repair, remanufacturing, recycling, composting, or other end-of-life pathways. Chemical information may also be incomplete or lost as materials move through value chains, and contaminants, degradation products, or reaction products may emerge during use and recycling. Considering chemical and material attributes during product design, use, and recovery may help identify and address potential barriers to circularity (OECD 2026a; UNEP 2021).

GSC considerations may relate to the three circular economy principles in the following ways:

1. **Eliminate waste and pollution.** Green chemistry emphasizes preventing pollution and reducing or eliminating the use or generation of hazardous substances through product and process design. Sustainable chemistry may broaden this evaluation to include material and energy use, resource

availability, life-cycle impacts, and other environmental, economic, and societal considerations. These approaches can inform efforts to prevent waste and pollution, but their effectiveness depends on the chemical, material, product, process, and application.

2. **Circulate products and materials**. Circularity seeks to retain the value of products, components, and materials through strategies such as maintenance, reuse, repair, refurbishment, remanufacturing, and recycling. The Ellen MacArthur Foundation distinguishes between technical cycles, in which products and materials are kept in use, and biological cycles, in which suitable materials may be returned safely to the biosphere. Chemical hazard, material compatibility, durability, reparability, separability, and the availability of recovery systems can affect whether these pathways are feasible. GSC can inform chemical and material selection and design decisions, but it does not ensure that a product can be safely or effectively circulated (Ellen MacArthur Foundation 2026).
3. **Regenerating nature**. Regenerating nature extends beyond using renewable feedstocks or preventing hazardous-substance use. It concerns shifting from the depletion and degradation of natural systems toward practices that restore soils, ecosystems, biodiversity, and other forms of natural capital. It may include returning appropriate biological materials safely to the environment and reducing demand for virgin resources by retaining products and materials in circulation. GSC may contribute to these objectives by reducing hazardous inputs and considering renewable feedstocks, resource use, biodegradability, and environmental fate. Use of renewable feedstock or a less hazardous chemical does not by itself demonstrate that a product or activity regenerates nature (Ellen MacArthur Foundation 2026).

Circularity can introduce tradeoffs that should be evaluated rather than assumed. Extending product life may conserve materials but prolong the use of legacy chemicals of concern. Recycling may reduce demand for virgin resources but may also recirculate substances of concern or introduce contaminants, degradation products, and reaction products into secondary materials. Recycling and other recovery processes also depend on collection systems, technologies, infrastructure, energy, and markets for recovered materials (OECD 2026a; UNEP 2026).

Consequently, decisions about circularity may need to consider chemical hazards, potential exposures, functional performance, material compatibility, product durability, resource and energy use, chemical traceability, recovery infrastructure, environmental fate, and impacts across the life cycle. The Organisation for Economic Co-operation and Development (OECD) identifies incomplete chemical information, heterogeneous waste streams, contaminants, degradation products, and limited traceability as challenges to ensuring chemical safety in recycled plastics. OECD concludes that safe and sustainable circularity for recycled plastics may require an integrated combination of standards, analytical methods, chemical traceability, incentives, and research collaboration (OECD 2026a).

GSC can therefore support circularity by informing the design and selection of chemicals and materials that are compatible with intended uses and recovery pathways. Circularity, in turn, provides a systems perspective for considering how products and materials retain value and move through the economy. Using the frameworks together may support more informed decisions, but applying one framework does not automatically satisfy the objectives or criteria of the other (UNEP 2026).

2 APPROACHES FOR EVALUATING CHEMICALS, PRODUCTS, AND PROCESSES AND APPLYING GREEN AND SUSTAINABLE CHEMISTRY

GSC uses multiple assessment and design approaches to inform decisions about chemicals, materials, products, and processes. These approaches address different questions and may be applied separately or together.

- **Alternatives assessment** compares potential substitutes or functional alternatives. (Section 2.1)
- **Life-cycle assessment (LCA)** evaluates potential environmental impacts associated with a defined product system across its life cycle. (Section 2.2)
- **Design for Environment (DfE)** incorporates environmental and human-health considerations into product or process design. (Section 2.3)
- **Design for End of Life (DfEOL)** focuses on the pathways available after a product or material no longer serves its intended function. (Section 2.4)

No single approach establishes that an option is universally safer or more sustainable. The appropriate approach, level of detail, and combination of tools depend on the decision context, available information, intended use of the results, and relevant performance, economic, environmental, and human-health considerations. The approaches described below can help identify tradeoffs and reduce the likelihood that an improvement in one area shifts impacts to another life-cycle stage, population, or environmental medium.

2.1 Alternatives Assessment

Alternatives assessment is a structured process for identifying, comparing, and selecting or supporting the development of alternatives to a chemical of concern (ECOS 2026). Potential alternatives may include chemical substitutes, changes in materials or processes, functional design changes, different technologies, or elimination of an unnecessary function. Depending on the framework and decision context, comparison criteria may include hazard, exposure potential, performance, technical feasibility, and economic viability (IC2 2025; National Research Council 2014; OECD 2021).

An alternatives assessment informs a decision; it does not ensure that the “safest” option will be selected. Results depend on the alternatives considered, the assessment scope, the criteria and weighting used, the quality and completeness of available data, and the assumptions applied. Data gaps may be particularly important when an alternative is new or less well characterized. The term safer is therefore comparative and should be linked to the attributes, uses, and exposure scenarios evaluated (OECD 2021).

Alternatives-assessment frameworks may be fit for purpose. An initial screen may focus on a limited set of criteria, while a more detailed assessment may evaluate additional attributes or scenarios. Hazard assessment is an important component, but hazard alone may not address exposure, performance, technical feasibility, cost, or potential life-cycle tradeoffs. Related tools, including exposure assessment, life-cycle assessment, cost analysis, and social assessment, may be used when relevant to the decision (Bechu et al. 2024; OECD 2026b).

Voluntary certification programs, hazard-assessment tools, government resources, chemical-management systems, and supplier information are among the information sources that may be used to identify or screen alternatives. These resources differ in purpose, scope, criteria, and level of review. A

product list or certification may provide useful information, but it is not a substitute for evaluating the specific function, use conditions, exposures, performance needs, and tradeoffs relevant to a decision (ECOS 2026; USEPA 2025b).

2.2 Life-Cycle Assessment

LCA is a method for evaluating potential environmental impacts associated with a defined product system. Depending on the goal and scope, an LCA may examine stages such as raw-material acquisition, manufacturing, transportation, use, and end-of-life management. The system boundary may cover the full life cycle or a defined portion of it. Because results depend on the study goal, functional unit, system boundaries, data, allocation choices, impact-assessment methods, and assumptions, the scope and limitations should be stated clearly.

ISO 14040 establishes the principles and framework for LCA, and ISO 14044 provides requirements and guidelines. The standards identify four interrelated phases (ISO 2006a, 2006b):

- Goal and scope definition establishes the intended application, reasons for the study, audience, functional unit, system boundaries, data requirements, and other methodological choices.
- Life-cycle inventory analysis compiles and quantifies relevant inputs and outputs within the defined system, such as materials, energy, products, emissions, and wastes.
- Life-cycle impact assessment evaluates the potential environmental significance of inventory results using selected impact categories and characterization methods.
- Interpretation evaluates the findings, limitations, consistency, and sensitivity of results and develops conclusions that are consistent with the stated goal and scope.

LCA can help identify stages or processes that contribute substantially to selected potential environmental impacts and can reveal potential tradeoffs across a product system. It does not, however, automatically determine which option is preferable. Meaningful comparisons require consistent functional units, system boundaries, data-quality expectations, assumptions, allocation procedures, and impact-assessment methods. LCA results also reflect the impact categories and methods included in the study and may not fully characterize chemical hazards, site-specific exposures, social conditions, economic feasibility, or technical performance unless those considerations are included through the study scope or additional analyses (ISO 2006a, 2006b; USDOE 2022a).

The Federal LCA Commons is a central access point for U.S. federal life-cycle inventory data and related repositories. It can support inventory development but is not itself an LCA standard or methodology (Federal LCA Commons, n.d.). Greenhouse-gas accounting standards and tools may also inform climate-related inventories, but an assessment limited to greenhouse-gas emissions is not a complete multi-impact LCA.

2.3 Design for Environment

DfE is a design approach that incorporates environmental and human-health considerations into the development or redesign of products, processes, and services (USEPA 1993). In this Focus Sheet, DfE refers to the general design approach rather than to a particular program, certification, or product label that uses the same or similar terminology.

DfE applies life-cycle thinking during design, when decisions about function, materials, chemistry, manufacturing, packaging, use, maintenance, and end-of-life pathways may still be changed. Relevant considerations may include chemical hazards and potential exposures, material and energy use, emissions and wastes, durability, repair, and compatibility with intended recovery or disposal systems.

The design objective and the relative importance of these considerations depend on the product, process, intended function, and decision context (USEPA 1993, 2020).

DfE is broader than selecting an individual chemical substitute. It may involve changing a product's formulation, material, component, manufacturing process, packaging system, use pattern, or method of delivering the required function. Depending on the design objective and decision context, relevant considerations may include chemical hazards and potential exposures, material and energy use, emissions and wastes, performance, technical feasibility, user needs, costs, and applicable requirements (USEPA 1993). Alternatives assessment and LCA may provide information for these design decisions, but neither tool replaces the broader design process (ISO 2006a, 2006b; OECD 2021).

2.4 Design for End of Life

DfEOL considers, during product and process design, what may happen when a product, component, or material no longer serves its intended function. Potential pathways include continued use, maintenance, repair, reuse, refurbishment, remanufacturing, disassembly, recycling, recovery, treatment, and disposal. DfEOL is a focused application of life-cycle design and is closely related to the circularity considerations described in Section 1.5.

Relevant DfEOL considerations may include the following:

- expected service life
- material composition and compatibility
- hazardous additives
- ease of maintenance or disassembly
- separation of components
- labeling and information availability
- collection and recovery infrastructure
- contamination
- degradation conditions
- potential exposures to workers, communities, and the environment.

Design choices may facilitate a pathway, but they do not ensure that the pathway will be available, economically viable, environmentally preferable, or properly used in practice (OECD 2026a; Plant et al. 2010; USEPA 1993).

DfEOL should consider the intended use and realistic end-of-life conditions rather than assume that a preferred pathway will be available or environmentally preferable. For example, designing a product for recyclability may have limited practical effect where collection, sorting, or appropriate recycling infrastructure is unavailable (UNEP 2026; Wu et al. 2025). Extending product life may conserve resources, but continued use or circulation of products containing legacy substances of concern may create other considerations that should be evaluated. In recycled plastics, substances of concern, contaminants, degradation products, and reaction products may complicate chemical characterization and subsequent use (OECD 2026a). Claims involving biodegradation or composting should identify the conditions under which degradation is expected to occur and consider the potential environmental fate of the material and its degradation products (Fiandra et al. 2023). These examples illustrate why end-of-life design decisions may need to consider chemical hazards, potential exposures, performance, recovery infrastructure, degradation conditions, and life-cycle tradeoffs.

2.5 How the Approaches Differ and Complement One Another

The four approaches described in Sections 2.1–2.4 are related, but they are not interchangeable. Each begins with a different decision question and produces different types of information. Using more than one approach may provide a more complete understanding of alternatives and tradeoffs. Table 2-1 summarizes the primary purpose and typical considerations of each approach and illustrates how the approaches may complement one another. The comparison is intended as a general guide; the scope and application of each approach may vary depending on the decision context, framework, and information available.

Table 2-1. Comparison of approaches for evaluating and designing chemicals, products, and processes.

Approach	Primary Question	Typical Considerations	Relationship to Other Approaches
Alternatives assessment	How do potential substitutes or functional alternatives compare for a defined use?	Hazard, exposure potential, performance, technical feasibility, and economic viability; other attributes as relevant.	May use LCA or other analyses to examine life-cycle, cost, or social tradeoffs.
Life-cycle assessment	What potential environmental impacts are associated with a defined product system?	Goal and scope, functional unit, system boundaries, inventory flows, impact categories, assumptions, and uncertainty.	Can inform alternatives assessment and design by identifying potential shifts in environmental impacts across life-cycle stages.
Design for Environment	How can environmental and human-health considerations be incorporated into design?	Function, chemistry, materials, manufacturing, use, resource demands, exposures, wastes, and life-cycle implications.	May use alternatives assessment and LCA results to guide design choices.
Design for End of Life	How can design account for realistic pathways after intended use?	Service life, repair, reuse, disassembly, material separation, recycling, recovery, treatment, disposal, infrastructure, and downstream exposure.	Applies DfE and circularity thinking specifically to end-of-life pathways and tradeoffs.

Source: Table developed by ITRC with assistance from Microsoft Copilot based on the sources cited in Sections 2.1 through 2.4, including, but not limited to ISO 14040 and ISO 14044 (ISO 2006a, 2006b), OECD guidance on safer chemical alternatives (OECD 2021), USEPA life-cycle design guidance (USEPA 1993), ECOS Resolution 17-1 ((ECOS 2026)), and (Plant et al. 2010). Copilot-generated content was reviewed and edited by ITRC for technical accuracy, scope, and consistency.

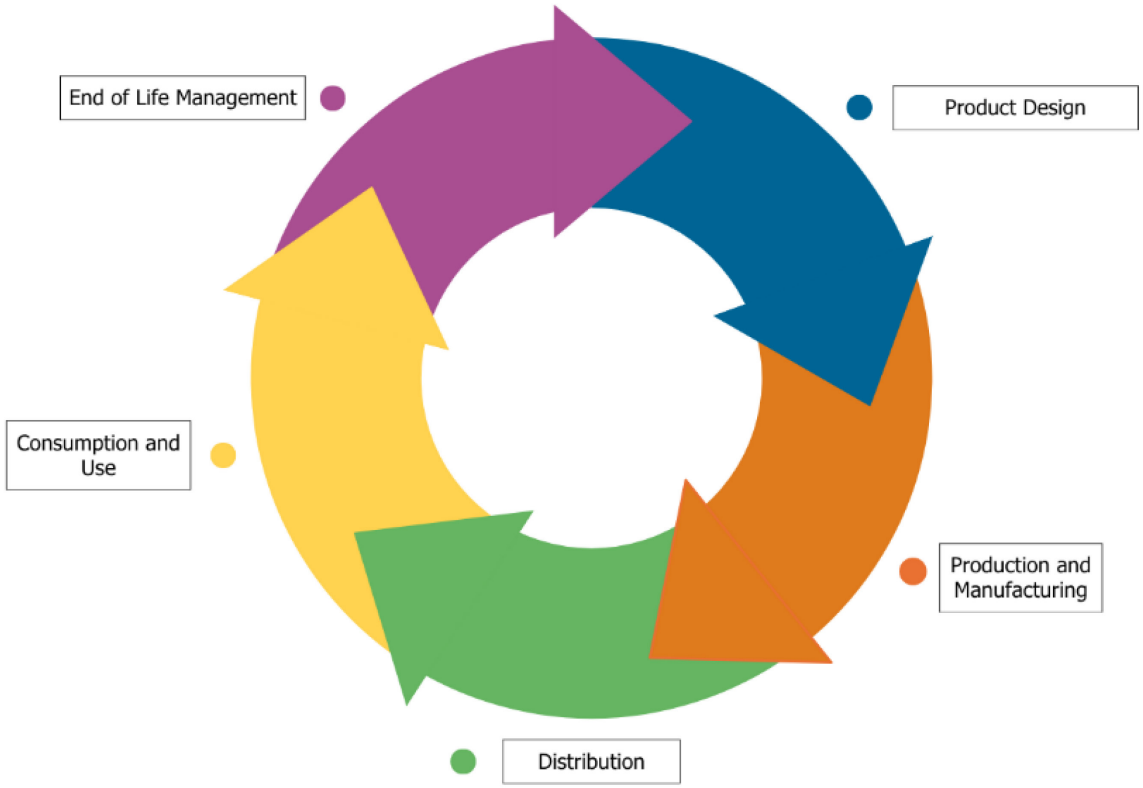
The approaches may be applied iteratively. An alternatives assessment may identify and compare candidate options; LCA may evaluate selected potential environmental impacts and tradeoffs; and DfE may use those findings to inform modification of a product or process. DfEOL may then examine whether the design is compatible with realistic maintenance, reuse, disassembly, recovery, treatment, or disposal pathways. Findings from any step may lead to reconsideration of the alternatives, assessment scope, design criteria, assumptions, or available data (OECD 2021; USEPA 1993, 2020).

The approaches may also produce findings that point in different directions. An option with a more favorable hazard profile may have less favorable results for another relevant attribute; an option with lower modeled impacts for selected LCA categories may be difficult to repair or recycle; or a design intended for recovery may not be compatible with available collection, processing, or recovery infrastructure. Such differences do not necessarily indicate that one approach is incorrect. They may reflect differences in the questions, criteria, system boundaries, assumptions, data, and methods used. The basis for the findings, along with important limitations and uncertainties, should therefore be made transparent to decision-makers (ISO 2006a, 2006b; OECD 2021, 2026a).

Accordingly, the purpose of using these approaches is not to assign a universal label to a chemical, product, or process. Their value is in structuring a decision, documenting assumptions and limitations, comparing relevant attributes, and identifying potential tradeoffs and information gaps. The selection and combination of approaches should be proportionate to the decision and consistent with the terminology and cautions established in Section 1.

3 GREEN AND SUSTAINABLE CHEMISTRY ACROSS THE PRODUCT LIFE CYCLE

Green chemistry and sustainable chemistry considerations may arise at multiple product life-cycle stages (Figure 3-1), including product design, production and manufacturing, distribution and packaging, consumption, use and procurement, and end-of-life management (USEPA 1993, 2026b).



Note: The circular arrangement illustrates connections among the stages; it does not imply that every product or material is recovered or returned to production.

Figure 3-1. Illustrative stages of a product life cycle.

The stages described in this section provide an organizing framework rather than a required sequence or a complete assessment method. Activities and impacts may overlap stages, and feedback from later stages may inform earlier design choices. The relevance of a particular consideration depends on the product, process, function, system boundary, and decision context. Applying a GSC approach at one stage does not establish that the product or process is preferable across its full life cycle (ISO 2006a, 2006b; USEPA 1993).

The selected case studies introduced in this section and included in Appendix A summarize how organizations and researchers have applied particular concepts. Inclusion does not constitute endorsement by ITRC of a company, product, technology, claim, or approach. Case study findings may be

specific to the application, data, assumptions, scale, and source used. Readers should consult the complete case study and underlying references before applying a conclusion in another context.

3.1 Product Design

Product design includes defining the intended function and performance requirements of a product and selecting the chemical formulation, materials, components, and product architecture. Design decisions can influence manufacturing conditions, potential exposures during use, durability, compatibility with packaging, and available end-of-life pathways (USEPA 1993).

GSC considerations may include chemical hazards, potential exposure, functional performance, material and energy requirements, feedstock options, durability, reparability, and compatibility with realistic recovery or disposal systems. Alternatives may have different hazard profiles, exposure potentials, performance characteristics, costs, availability, and life-cycle implications. Design choices should therefore be evaluated against the intended function and decision context rather than characterized as universally benign or sustainable. The approaches for evaluating chemicals, products, and processes described in Section 2 may inform these decisions (Anastas and Warner 1998; OECD 2021; UNEP 2021).

3.1.1 Selected Case Studies

Restricting Flame Retardants in Products: Examines concerns associated with selected brominated flame retardants in consumer products and the role of hazard, exposure, performance requirements, and alternatives assessment when considering restrictions or substitutions.

Cellulose-Based Plastic and Microplastic Formation: Examines a cellulose-based polymer design intended to change how a material behaves after use. The complete case study identifies the material composition, disassembly conditions and time frame, test environments, constituent-release considerations, and evidence used to evaluate microplastic formation.

Regrettable Substitution in Selected "BPA-Free" Products: Examines substitution of bisphenol A (BPA) with structurally related chemicals and illustrates why a "free-of" claim does not establish that an alternative has a more favorable hazard or exposure profile.

Fiber-Based Alternatives to Selected Single-Use Plastics: Examines molded-fiber tableware produced from sugarcane bagasse and bamboo and the relationship among feedstock selection, material composition, chemical additives, food-contact performance, manufacturing, and the conditions required for composting or degradation.

Alternative Thermal-Paper Imaging Technology: Examines a thermal-paper imaging approach intended to avoid bisphenol-based color developers and considers how a change in imaging mechanism may affect hazard, exposure, performance, and downstream paper recovery.

3.2 Production and Manufacturing

Production and manufacturing include sourcing and preparing raw materials, conducting chemical or biological transformations, separating and purifying products, and assembling or formulating finished products. Packaging undertaken at the manufacturing facility may overlap this stage and the distribution stage (USEPA 1993).

Relevant GSC considerations may include hazards of feedstocks, reagents, solvents, catalysts, intermediates, and byproducts; process conditions; atom economy; yield and selectivity; energy and water use; worker exposure; emissions; waste generation; and accident prevention. Green chemistry principles

also address waste prevention, incorporation of starting materials into the final product, less hazardous syntheses, safer solvents and reaction conditions, energy efficiency, and renewable feedstocks where technically and economically practicable (Anastas and Warner 1998; USEPA 2026b). Whether a process change produces a net improvement depends on its performance, scale, inputs, outputs, and life-cycle tradeoffs.

3.2.1 Selected Case Studies

Renewable and Waste-Derived Biopolymers for Water Treatment, Agriculture, and Material Applications: Examines production and use of renewable or waste-derived biopolymers for selected water-treatment, agricultural, or material applications. Conclusions about performance, waste, pollution, cost, and resource use should be tied to the specific formulation, application, test conditions, source, and comparison used in the complete case study.

Continuous Bioprocessing Innovation: Examines a transition from batch processing to an integrated continuous bioprocess for a pharmaceutical product and considers production capacity, process efficiency, equipment footprint, material and energy requirements, water use, consumables, waste generation, product quality controls.

3.3 Distribution and Packaging

Distribution and packaging include preparation for shipment, storage, transportation, wholesale and retail handling, and delivery to an end user. Packaging may protect product quality, control exposure, communicate safe-use information, and support transportation and handling. Packaging also introduces materials and additives that may affect resource use and downstream recovery (UNEP 2019, 2022; USEPA 1993).

Relevant considerations may include product concentration, packaging weight and volume, chemical compatibility, barrier properties, additive selection, potential migration, durability, damage prevention, transport conditions, and compatibility with reuse, recycling, or other recovery systems. Product concentration or lighter packaging may reduce mass or volume transported, but the magnitude and significance of any resulting benefit depend on the product, packaging system, shipping distance, mode of transport, use requirements, product loss or damage, and end-of-life pathway. Packaging decisions involve chemists, material scientists, engineers, product designers, manufacturers, distributors, and recovery-system participants (UNEP 2019, 2022; USEPA 1993).

3.3.1 Selected Case Study

Mycelium-Based Alternative to Expanded Polystyrene Packaging: Examines a protective packaging composite made from fungal mycelium and minimally processed hemp biomass. Relevant comparisons include compressive and protective performance, feedstock and manufacturing requirements, energy and emissions, moisture sensitivity, transportation, scalability, and realistic end-of-life pathways.

3.4 Consumption, Use, and Procurement

The use stage begins when a product or chemical is acquired and includes storage, handling, application, maintenance, and operation until the product no longer serves its intended function. Conditions of use can affect exposure, performance, energy or water consumption, releases, durability, and the quantity and characteristics of residual materials (ISO 2006a, 2006b; USEPA 1993).

Relevant considerations may include instructions and training, dilution or application rates, chemical compatibility, ventilation and other exposure controls, maintenance, expected service life, emissions or releases during use, and management of unused products (USEPA 1993). Product labels, standards, and ecolabels may provide information about selected attributes, but their scope, criteria, verification procedures, and intended uses vary. A label or certification should therefore be interpreted according to the attributes, product categories, and conformity-assessment procedures it addresses (USEPA 2026d).

Procurement is a decision process within this stage rather than a separate life-cycle stage. Environmentally preferable purchasing incorporates environmental considerations, along with price and performance, when comparing products or services that serve the same purpose. USEPA encourages a life-cycle and multiattribute perspective and provides recommendations on standards and ecolabels for federal purchasing (USEPA 1999, 2026a).

3.5 End-of-Life Management

End-of-life management begins when a product, component, or material no longer serves its intended function. Potential pathways include continued use, repair, reuse, refurbishment, remanufacturing, disassembly, recycling, recovery, treatment, and disposal. End of life does not necessarily end with successful recovery into a new production cycle; the actual pathway depends on product condition, chemical and material composition, collection and processing systems, technical feasibility, economics, applicable requirements, and user behavior (UNEP 2021; USEPA 1993).

Relevant GSC considerations may include substances of concern, material compatibility and separability, residual product, worker and community exposure, process inputs and emissions, treatment residuals, destruction or transformation products, chemical traceability, and the availability of collection and recovery infrastructure. Recycling or recovery may conserve resources but may also recirculate substances of concern or introduce contaminants or degradation products into secondary materials. These tradeoffs should be evaluated for the specific material and pathway (OECD 2026a; UNEP 2021).

Extended producer responsibility (EPR) is a policy approach that assigns producers financial or physical responsibility for specified aspects of a product's life cycle, which may include management or disposal of post-consumer products. EPR requirements vary by jurisdiction and product category. In the United States, state programs may address products such as packaging, batteries, electronics, mattresses, tires, and paint (Product Stewardship Institute 2026; USEPA 2026c).

3.5.1 Selected Case Study

Nickel Catalyst for Polyolefin Recycling: Examines research-scale catalytic hydrogenolysis of selected polyolefin waste streams using a nickel catalyst. Relevant evaluation considerations include feed composition and pretreatment, tolerance of contaminants, catalyst performance and regeneration, reaction temperature and pressure, hydrogen and energy requirements, product yields and quality, residuals, scale, and comparison with other management pathways.

3.6 Applications That Span or Extend Beyond Individual Life-Cycle Stages

Some GSC applications do not fit neatly within one product life-cycle stage. An application may involve decisions and potential impacts across several stages, or it may involve an environmental treatment or remediation function that is not part of the conventional life cycle of the product or chemical that contributed to contamination (USEPA 1993, 2026b). The following examples are included to illustrate

these broader applications. Their placement in this subsection does not indicate that the two technologies serve similar functions or should be evaluated using the same criteria.

3.6.1 Sustainable Aviation Fuel

Sustainable aviation fuel (SAF) illustrates an application that may involve considerations across multiple life-cycle stages. Relevant considerations may include feedstock production and collection, conversion chemistry, process energy, transportation and blending, infrastructure and aircraft compatibility, fuel use, and life-cycle greenhouse-gas accounting. The U.S. SAF Grand Challenge includes a goal of at least a 50 percent reduction in life-cycle greenhouse-gas emissions compared with conventional jet fuel. Results for a particular pathway depend on factors such as the feedstock, conversion process, energy inputs, system boundary, allocation choices, and accounting method (USDOE 2022b, 2026).

3.6.1.1 Selected Case Study

Sustainable Aviation Fuel: Examines selected SAF production pathways and the feedstocks, chemical processes, performance requirements, infrastructure considerations, and life-cycle greenhouse-gas factors associated with producing fuels compatible with existing aviation systems. The example does not establish that all SAF pathways provide the same environmental or emissions performance.

3.6.2 Regenerable Treatment Material for Selected PFAS

Environmental treatment and remediation are generally distinct from green chemistry's emphasis on preventing hazardous substances from being used or generated. Nevertheless, GSC considerations may inform the design and operation of a treatment technology, such as the hazards of treatment chemicals, material and energy use, treatment effectiveness, regeneration, residual generation, and potential transformation products (USEPA 2026b, 2012) A regenerable treatment material may be designed to capture selected contaminants and permit repeated use of the treatment medium. Evaluation should distinguish among contaminant capture, contaminant destruction or transformation, regeneration of the treatment material, and management of treatment residuals.

3.6.2.1 Selected Case Study

Regenerable Treatment Material for Selected PFAS: Examines a copper-aluminum material evaluated for capture of selected anionic PFAS from water, followed by thermal treatment intended to regenerate the material and partially defluorinate adsorbed PFOA. Relevant evaluation considerations include the PFAS compounds and water matrices tested, capture effectiveness, fluorine mass balance, residual PFAS and transformation products, energy and reagent requirements, residuals, regeneration cycles, treatment capacity, and scale. The example concerns treatment-material use and regeneration; it is not an example of managing the original PFAS-containing product at the end of its useful life.

3.7 Interpreting the Examples Across Life-Cycle Stages

The selected examples illustrate that a change made at one life-cycle stage can affect other stages. A material selected to reduce a chemical hazard may require different manufacturing conditions. A concentrated product may change packaging, transport, dilution, and use requirements. A durable product may remain in service longer but retain legacy substances of concern. A product designed for recycling may not be recovered if collection or processing infrastructure is unavailable (OECD 2021, 2026a; UNEP 2021; USEPA 1993).

For this reason, the examples should be interpreted using the approaches described in Section 2. Alternatives assessment can compare potential substitutes for a defined function; LCA can evaluate

selected potential environmental impacts across a defined product system; DfE can incorporate environmental and human-health considerations into design; and DfEOL can examine realistic pathways after intended use. The appropriate combination depends on the decision and available information. No single example demonstrates that a product or technology is universally safer, circular, or sustainable.

4 FEDERAL AND STATE POLICY AND PROGRAM LANDSCAPE

Federal and state statutes, regulations, policies, and programs can influence research, chemical and product design, manufacturing, disclosure, purchasing, use, and end-of-life management. Some establish enforceable requirements; others provide research coordination, technical assistance, voluntary certification, data, procurement tools, or incentives.

This section provides an overview of selected federal authorities and programs and describes common types of state actions. It is not a comprehensive inventory and does not determine the applicability of any authority to a particular chemical, product, facility, or activity. Inclusion of an example does not constitute ITRC endorsement, and omission does not indicate that a law or program is less important. Requirements and program details may change. Readers should consult the current statute, regulation, agency guidance, and responsible agency before relying on this summary.

The ITRC Team created the **Green and Sustainable Chemistry Resource Table**, which provides additional examples and source links. The Table is available to download at **http://www.itrcweb.org/green-sustainable-chemistry/**. It is accurate as of the date of publication and should not be treated as a complete or permanent list that is routinely updated.

4.1 Federal Statutory and Program Landscape

4.1.1 Sustainable Chemistry Research and Development Act

The Sustainable Chemistry Research and Development Act was enacted as Subtitle E of Title II of the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021, Public Law 116-283, 134 Statute 3388, on January 1, 2021. The provisions are codified at 15 U.S.C. §§ 9301–9306. The law directs the Office of Science and Technology Policy to convene an interagency entity under the National Science and Technology Council (NSTC) to coordinate federal programs and activities in support of sustainable chemistry. It also addresses a strategic plan, agency activities, partnerships, prioritization, and related matters.

The statute provides a federal coordination and research-and-development framework. It does not create a general product-approval program or establish that a chemical, product, or process meeting a single attribute is sustainable. Agencies participating in the federal effort may incorporate sustainable chemistry into research, development, demonstration, technology transfer, commercialization, education, and training activities within their respective authorities and programs.

In December 2024, NSTC published the Federal Sustainable Chemistry Strategic Plan. The plan identifies strategic goals and cross-cutting themes for federal sustainable chemistry activities. It is a federal strategy document and should not be described as a product standard, certification, or generally applicable regulatory requirement (NSTC 2024).

4.1.2 Safer Choice

Safer Choice is a voluntary USEPA pollution prevention program that helps consumers, businesses, and purchasers identify products that meet program requirements. The Safer Choice and Design for the Environment Standard establishes requirements that products and their ingredients must meet to earn the Safer Choice label or Design for the Environment logo. The program evaluates ingredients against applicable human-health and environmental criteria and also addresses product performance, ingredient disclosure, packaging, and other product-level requirements (USEPA 2026f, 2026e).

The number and identity of certified products change over time. Readers can use USEPA's searchable list of products that currently meet the Safer Choice Standard. Certification applies to the reviewed product under the program's requirements; it should not be interpreted as a general finding that the product has no hazards or is preferable for every use or life-cycle consideration (USEPA 2026g).

4.1.3 Safer Chemical Ingredients List

The Safer Chemical Ingredients List (SCIL) is organized by functional-use class and contains chemical ingredients evaluated by the Safer Choice Program. Listed chemicals have different status designations reflecting the program's evaluation. The list is not exclusive, does not include confidential chemicals, and may change as new information or innovations become available (USEPA 2026e).

SCIL can help formulators identify ingredients that may meet Safer Choice ingredient criteria for a functional use. Inclusion of an ingredient on the SCIL does not authorize a use under other statutes and does not entitle a product to display the Safer Choice label. A product must complete the applicable third-party review and meet ingredient- and product-level requirements before it may qualify for the label (USEPA 2026e).

4.1.4 USDA BioPreferred Program

The U.S. Department of Agriculture (USDA) administers the BioPreferred Program under section 9002 of the Farm Security and Rural Investment Act of 2002, as amended. The program includes federal purchasing requirements for designated categories of biobased products and a voluntary certification and labeling program. Implementing requirements are provided in 7 Code of Federal Regulations part 4270. The program also maintains a searchable catalog of qualified and USDA Certified Biobased Products (USDA 2026).

The USDA Certified Biobased Product label verifies that a product contains a specified amount of biobased content under the program's requirements. It does not establish that the product has lower chemical hazards, lower life-cycle impacts, or preferable performance across all relevant attributes. Biobased content is one product characteristic and should be interpreted together with other applicable health, environmental, performance, and life-cycle considerations (USDA 2026).

4.1.5 Federal Research, Measurement, and Standards Activities

Federal agencies support sustainable chemistry and related circular economy work through research funding, measurement science, data, standards, research infrastructure, education, and partnerships. The U.S. National Science Foundation supports research, infrastructure, workforce development, and partnerships related to sustainable chemistry (U.S. National Science Foundation 2024). The National Institute of Standards and Technology (NIST) supports circular economy implementation through measurement science, standards, reference materials, data, and decision tools. Its Circular Economy Program and Circular Economy Standards Registry address subjects such as secondary-material characterization and performance, data consistency, product and material recovery, and standards

relevant to circular supply chains (NIST 2026a, 2026b). Additional research solicitations, grants, prizes, and cooperative agreements administered by various federal departments and agencies may be available as government and program priorities change (GSC 2026).

4.1.6 Other Relevant Federal Authorities and Resources

Other federal statutes and programs may influence chemical manufacture, reporting, risk evaluation and management, pollution prevention, releases, waste management, and purchasing. Examples include the Toxic Substances Control Act, the Pollution Prevention Act, the Toxics Release Inventory, and federal environmentally preferable purchasing requirements and resources. These authorities and programs have different purposes and scopes and should not be interpreted as a single federal GSC framework.

Federal departments and agencies also administer product- or sector-specific authorities and provide technical assistance, data, research, and commercialization support. Additional examples are included in the **Green and Sustainable Chemistry Resource Table** available on the ITRC website at **http://www.itrcweb.org/green-sustainable-chemistry/**. Current information should be obtained from the responsible department or agency.

4.2 Types of State Actions Landscape

States use a range of statutory, regulatory, procurement, technical assistance, and other approaches. A state program or authority may use more than one approach, and the categories below are not mutually exclusive. Programs with similar names may differ in legal authority, chemicals or products covered, responsible entities, exemptions, implementation schedules, and enforcement.

- **Reduction of toxics use and pollution prevention.** Requirements or assistance programs may address facility chemical use, source reduction, planning, reporting, fees, or technical assistance.
- **Chemical or product reporting and transparency.** States may require manufacturers or other entities to report chemicals in products, facility use, releases, or other information.
- **Priority chemicals and products.** Some states establish processes to identify chemicals or chemical classes of concern and product categories for further evaluation or regulatory action.
- **Alternatives assessment.** A law or program may require or support comparison of potential substitutes, process changes, or functional alternatives.
- **Product restrictions or prohibitions.** States may restrict a chemical or class in specified products, establish concentration limits, prohibit intentionally added substances, or phase requirements in over time.
- **Procurement.** State purchasing policies may incorporate specifications, standards, ecolabels, chemical restrictions, recycled content, or life-cycle and multiattribute considerations.
- **Packaging, stewardship, and EPR.** State programs may address packaging design, labeling, recycled content, collection, recycling, or producer responsibility.
- **Technical assistance, research, education, or incentives.** States may offer grants, recognition, training, technical assistance, research partnerships, or assistance with pollution prevention and safer alternatives.

4.3 Resources for Current State Information

Searchable resources maintained by the National Conference of State Legislatures (NCSL), Interstate Chemicals Clearinghouse (IC2), Product Stewardship Institute (PSI), and other organizations may help

users identify state activity, but entries should be verified against primary state sources before use. No single database captures every state statute, regulation, policy, program, amendment, and implementation update. The following resources can supplement the **Green and Sustainable Chemistry Resource Table**:

- **National Conference of State Legislatures (NCSL), Environment and Natural Resources Legislation.** Includes state legislation identified by NCSL staff and indicates measure status, such as enacted, pending, or failed. Users should verify current bill text and status with the relevant legislature (NCSL 2026).
- **Interstate Chemicals Clearinghouse (IC2).** Provides state-focused resources that include links to chemicals-in-products reporting systems, alternatives-assessment materials, procurement resources, and other state information (IC2 2026).
- **Product Stewardship Institute (PSI), EPR resources.** Provides information on enacted state EPR and product stewardship laws. Current statutes, regulations, and agency materials should be consulted for requirements (Product Stewardship Institute 2026).

4.4 Selected State Examples

The following examples illustrate different state approaches and are included in **Appendix B**. Their inclusion does not indicate that ITRC has ranked them above other state programs. The linked case studies provide additional statutory, regulatory, and implementation details.

Washington State Department of Ecology, Safer Products Restrictions and Reporting Rule: Illustrates a state framework that applies restrictions or reporting requirements to specified priority chemical-consumer product combinations.

Minnesota Pollution Control Agency, PFAS in Products and Amara's Law: Illustrates product reporting requirements, category-specific restrictions, a phased broader prohibition, and Minnesota's rulemaking process for determining currently unavoidable uses of intentionally added PFAS.

California Department of Toxic Substances Control, Safer Consumer Products Program: Illustrates a state framework that identifies specified product-chemical combinations as Priority Products, requires responsible entities to evaluate alternatives, and authorizes regulatory responses based on the alternatives analysis and other available information.

5 IMPLEMENTATION CONSIDERATIONS

Implementation of GSC may involve technical, informational, economic, supply-chain, infrastructure, regulatory, and organizational considerations. Their relevance and relative importance depend on the chemical, product, process, function, organization, and decision context. This section describes factors that may affect implementation. It does not prescribe a sequence of actions or recommend adoption of a particular program, tool, technology, or policy.

The considerations below draw from the assessment and design approaches discussed in Section 2, the life-cycle applications discussed in Section 3, and selected external sources. Published findings and ITRC synthesis are identified separately where practical. An implementation challenge in one setting may be less relevant in another, and an apparent benefit may be accompanied by tradeoffs elsewhere in the product life cycle.

5.1 Technical and Performance Considerations

A potential alternative or process change must generally perform the required function under relevant conditions. Depending on the application, evaluation may include product quality, reliability, durability, compatibility, safety controls, process conditions, technical maturity, qualification requirements, and the ability to maintain performance at a larger scale. Performance requirements and acceptable tolerances may differ among users, sectors, and applications.

Testing at laboratory or pilot scale may not establish performance under full-scale manufacturing, distribution, use, maintenance, or end-of-life conditions. Changes in formulation, equipment, feedstock, process control, or scale may affect yield, byproducts, energy and water use, worker exposure, emissions, product consistency, and waste. Alternatives assessment and LCA can provide information for these decisions, but neither replaces application-specific engineering, validation, or quality requirements (NSTC 2024; OECD 2021).

5.2 Data and Information Considerations

Implementation decisions may require information about chemical identity, composition, function, hazard, exposure potential, performance, quantities, suppliers, manufacturing conditions, product use, and end-of-life pathways. Relevant information may be incomplete, confidential, inconsistent across suppliers, unavailable for newer alternatives, or difficult to transfer through complex value chains. Data gaps can limit comparison of alternatives or create uncertainty about whether an apparent improvement shifts hazards or impacts elsewhere (NSTC 2024; OECD 2021).

Assessment frameworks and tools differ in scope, data requirements, treatment of uncertainty, and methods for addressing hazard, exposure, life-cycle, economic, and social considerations. OECD guidance identifies minimum considerations for selecting safer chemical alternatives, and the OECD Substitution and Alternatives Assessment Toolbox compiles multiple frameworks and supporting resources. The continued existence of multiple approaches does not imply that one framework is appropriate for every decision (OECD 2021, 2026b).

Bechu et al. (2024) identified continuing research and practice needs in alternatives assessment, including comparative exposure, life-cycle integration, decision analysis, mixtures, and practical treatment of tradeoffs. Documentation of data sources, assumptions, uncertainty, exclusions, and decision criteria can help users understand the basis and limits of an assessment, but documentation does not eliminate underlying data gaps.

5.3 Cost, Scalability, and Infrastructure

Costs may arise from research and development, testing, reformulation, equipment changes, process validation, certification, regulatory review, supplier qualification, workforce training, data collection, production transition, and end-of-life management. Potential savings may arise from reduced material or energy use, improved process efficiency, reduced waste-management demands, or lower exposure to selected future risks. The timing, allocation, and magnitude of costs and benefits can differ among manufacturers, suppliers, purchasers, users, governments, and waste-management organizations (Golden et al. 2021; Tickner and Cattermole 2022).

An alternative that is technically feasible at one scale may face different constraints at commercial scale. Relevant factors may include access to capital, production capacity, feedstock availability and consistency, equipment, utilities, quality control, logistics, market demand, and the availability of collection, recycling, composting, treatment, or disposal infrastructure. Commercialization studies of green chemistry technologies describe scale-up, market adoption, value-chain coordination, and

displacement of incumbent technologies as context-dependent processes rather than automatic outcomes (Golden et al. 2021; Tickner and Cattermole 2022).

Life-cycle cost information may be useful, but comparisons depend on the scope, time horizon, baseline, allocation of costs, discounting, and assumptions about future conditions. A lower purchase price does not necessarily indicate a lower total cost, and a higher initial cost does not by itself establish a net benefit over the product or process life cycle (Golden et al. 2021; OECD 2021).

5.4 Supply-Chain Considerations

Implementation may depend on the availability, quality, traceability, and continuity of chemical, material, or feedstock supply. A technically suitable alternative may be available only from a limited number of suppliers, at insufficient volume, or with variable composition or specifications. Supplier changes may require qualification, testing, contractual changes, or modification of manufacturing and quality-control procedures (Golden et al. 2021; NSTC 2024; Tickner and Cattermole 2022).

Information can also be lost or become incomplete as chemicals, materials, and products move through supply chains. Confidential business information, inconsistent terminology, changes in formulation, and limited communication among suppliers, manufacturers, brands, purchasers, users, and recovery organizations may complicate assessment and implementation. Diversifying inputs or using renewable, recycled, or locally sourced materials may affect supply options, but does not by itself establish that an alternative is preferable across health, environmental, performance, cost, or life-cycle attributes (Golden et al. 2021; NSTC 2024).

5.5 Regulatory and Organizational Considerations

Regulatory authorities and voluntary programs may use different definitions, criteria, reporting systems, product scopes, exemptions, schedules, and documentation requirements. An organization operating in multiple jurisdictions may therefore encounter differing or overlapping requirements. As described in Section 4, regulations, program web pages, lists, standards, and implementation schedules can change and should be verified with the department, agency, or program responsible.

5.6 Existing Resources and Continuing Technical Needs

Existing programs and resources address some implementation needs without resolving every decision or data gap. Examples include voluntary product certification and screening programs such as USEPA Safer Choice and SCIL; USDA BioPreferred certification and procurement resources; alternatives-assessment guidance and tools maintained by OECD and IC2; federal and state research, technical-assistance, procurement, reporting, and funding programs; and NIST measurement and standards resources. Sections 2 and 4 describe selected examples and their limitations.

Published guidance and research continue to identify differences among assessment frameworks, gaps in hazard and exposure information, challenges integrating life-cycle and socioeconomic considerations, and needs involving data interoperability, measurement, workforce capacity, commercialization, and evaluation of tradeoffs (Bechu et al. 2024; NSTC 2024; OECD 2021).

5.7 Potential Tradeoffs and Unintended Consequences

A change intended to improve one attribute may perform less favorably against another. Potential tradeoffs can involve hazard, exposure, energy or water use, resource availability, emissions, waste, durability, performance, cost, equity, or end-of-life compatibility. A substitution may also shift an impact

from one population, environmental medium, geographic area, or life-cycle stage to another (NSTC 2024; OECD 2021; UNEP 2021).

Examples of potential unintended outcomes include replacing a chemical with a poorly characterized alternative, selecting a product that meets one certification or content criterion but performs less favorably against other relevant attributes, designing a material for recycling or composting where appropriate infrastructure is unavailable, prolonging use of a durable product that contains a legacy substance of concern, or withdrawing a product from a market when a compliant and technically feasible alternative is unavailable. These possibilities do not establish that a proposed change should or should not proceed; they identify questions that may need to be evaluated in the applicable decision context (NSTC 2024; OECD 2021; UNEP 2021).

6 KEY TAKEAWAYS

The principal points presented in this Focus Sheet are summarized below:

- **Green chemistry and sustainable chemistry are related but distinct concepts**. Green chemistry focuses primarily on designing chemical products and processes to reduce or eliminate the use or generation of hazardous substances. Sustainable chemistry considers a broader range of human-health, environmental, resource, economic, societal, and life-cycle factors. The combined term GSC does not indicate that every green chemistry practice satisfies every sustainable chemistry consideration.
- **Different assessment and design approaches answer different questions**. Alternatives assessment, LCA, DfE, and DfEOL may provide complementary information about potential alternatives, environmental impacts, design choices, and end-of-life pathways. No single approach establishes that a chemical, product, process, or technology is universally safer or more sustainable.
- **Chemical and material decisions are context dependent and may involve tradeoffs**. Relevant considerations may include hazard, exposure potential, functional performance, technical feasibility, cost, data quality, resource use, supply chains, infrastructure, and impacts across the life cycle. Conclusions may be affected by the alternatives evaluated, analytical boundaries, methods, assumptions, uncertainty, and the intended use of the results.
- **Governmental and voluntary programs use varied approaches**. Federal and state authorities and programs may involve research coordination, certification, ingredient screening, procurement, reporting, product restrictions, pollution prevention, technical assistance, funding, or standards and measurement resources. Their legal effect, scope, criteria, and implementation status differ, and current requirements should be verified with the responsible agency or program.
- **Examples and case studies illustrate selected applications rather than universally applicable conclusions.** Their findings may depend on the function, conditions of use, data, scale, comparison, infrastructure, and decision context. Inclusion in this Focus Sheet does not constitute ITRC endorsement, and a result observed in one application does not establish that the same product, technology, or approach is appropriate for every use or life-cycle stage.

Taken together, these points support transparent, fit-for-purpose evaluation of GSC options while recognizing data gaps, implementation constraints, and potential unintended consequences. The information in this document and companion resources can provide a common technical foundation for discussions and decisions involving chemicals, materials, products, and processes. Its concepts, approaches, examples, and resources should be applied in a manner appropriate to the specific question and decision context. As scientific information, technologies, governmental programs, and assessment

methods continue to develop, users should consult current sources and clearly document the information, assumptions, limitations, and tradeoffs that inform their conclusions.

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ACRONYMS

BPA	bisphenol A
DfE	Design for Environment
DfEOL	Design for End of Life
ECOS	Environmental Council of the States
EPR	Extended Producer Responsibility
ERIS	Environmental Research Institute of the States
GSC	green and sustainable chemistry
IC2	Interstate Chemicals Clearinghouse
ITRC	Interstate Technology & Regulatory Council
LCA	life-cycle assessment
NCSL	National Conference of State Legislatures
NIST	National Institute of Standards and Technology
NSTC	National Science and Technology Council
OECD	Organisation for Economic Co-operation and Development
PFAS	per- and polyfluoroalkyl substances
SAF	sustainable aviation fuel
SCIL	Safer Chemical Ingredients List
UNEP	United Nations Environment Programme
USDA	U.S. Department of Agriculture
USDOE	U.S. Department of Energy
USEPA	U.S. Environmental Protection Agency

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APPENDIX A. SELECTED CASE STUDIES

Product Design Case Study: Restricting Flame Retardants in Products

Purpose and Objective

This case study examines the use of selected brominated flame retardants in consumer products, their detection in U.S. breast milk, and the role that hazard assessment, exposure information, performance requirements, alternatives assessment, and life-cycle considerations may play when evaluating restrictions or substitutions.

Overview

Brominated flame retardants (BFRs) have historically been used in consumer products such as electronics, furniture foam, textiles, and plastics to meet flammability standards (Brandsma et al. 2022; Schreder and Uding 2019). Although these chemicals were intended to improve fire safety, some BFRs have been identified as persistent, bioaccumulative, and toxic (Agency for Toxic Substances and Disease Registry 2017). Research has demonstrated that these compounds migrate from products into indoor dust, air, food systems, and ultimately the human body (Alaee et al. 2003; Hammel et al. 2017). A study analyzing breast-milk samples from U.S. mothers detected multiple BFRs, including phased-out polybrominated diphenyl ethers (PBDEs) and replacement flame retardants. The data indicate continued exposure to legacy PBDEs and selected replacement flame retardants after phaseouts of certain PBDE formulations (Environmental Working Group 2003; Schreder et al. 2023).

In response to growing concerns regarding the persistence and toxicity of these chemicals, the U.S. Environmental Protection Agency (USEPA) supported the phaseout of several PBDE formulations, such as decabromodiphenyl ether (DecaBDE), through initiatives such as the Partnership to Evaluate Flame Retardant Alternatives to DecaBDE (USEPA 2026). States such as Washington have adopted safer products regulations restricting certain flame retardants in consumer products and electronic equipment (Safer Products Restrictions and Reporting, Washington Administrative Code, Chapter 173-337). This case study examines how product design, chemical selection, alternatives assessment, product use, and end-of-life management may influence potential hazards and exposures associated with flame-retardant chemicals.

Problem

Certain flame-retardant chemicals used in consumer products can persist in the environment and accumulate in human tissue. Detection in breast milk indicates a potential exposure pathway for nursing infants.

Responses and Considerations

The primary response to concerns surrounding BFRs involved a combination of voluntary industry phaseouts and regulatory restrictions targeting PBDEs, particularly the penta-, octa-, and deca-BDE formulations commonly used in furniture foam, electronics, textiles, and plastics. Phaseouts and restrictions were followed by reported declines in concentrations of certain PBDEs in breast milk, although the relative influence of individual regulatory, market, and exposure changes may be difficult to distinguish (Guo et al. 2016). A 2023 study also detected replacement flame retardants and bromophenols in breast milk, many of which were introduced with limited hazard and life-cycle evaluation

for which the available information regarding persistence, bioaccumulation, endocrine activity, or toxicity may vary (Schreder et al. 2023).

This case study highlights the importance of green and sustainable chemistry (GSC) principles through a systems-based approach that extends beyond simple chemical substitution. Although restrictions and phaseouts reduced exposure to legacy PBDEs, the development of replacement flame retardants illustrates the potential for regrettable substitution when alternatives are adopted without comprehensive hazard assessment, life-cycle analysis, safer material design, class-based chemical evaluation, and design for end-of-life management. These approaches may help compare potential substitutes and identify whether an alternative could shift hazards or impacts rather than reduce them.

Green and Sustainable Chemistry Across the Product Life Cycle

- **Product Design:** Selection of flame retardants involves performance requirements and compliance with flammability standards, sometimes with incomplete information about long-term toxicity, persistence, bioaccumulation, or exposure. Green chemistry tools such as hazard assessment and alternatives assessment can provide information for comparing potential alternative chemicals, materials, or design approaches early in the design process and help avoid the use of chemicals that may later require costly regulation or remediation.
- **Production and Manufacturing:** Manufacturing and incorporation of BFRs into products may create opportunities for occupational exposure, emissions, and waste generation. Relevant GSC considerations include chemical and process hazards, potential exposures, process inputs, emissions, and byproducts. Sustainable chemistry approaches promote safer synthesis methods, reduce hazardous inputs, and encourage the use of inherently safer chemicals and processes.
- **Distribution and Consumer Use:** Flame retardants used in electronics, furniture, and textiles can migrate into indoor dust and air during normal product use. The study detected legacy PBDEs, selected replacement flame retardants, and bromophenols in breast milk after phaseouts of certain PBDE formulations, indicating that exposure can continue through products still in use and contaminants already present in indoor and broader environments.
- **End-of-Life Management:** Products containing BFRs can continue releasing hazardous substances during disposal, recycling, or waste processing and may enter recycling streams, treatment residuals, or the environment, depending on the product and management pathway. GSC emphasizes designing products that avoid hazardous additives and are compatible with realistic reuse, recycling, treatment, or disposal pathways at end of life.

Outcomes and Potential Impacts

Human Exposure Findings and Health Considerations:

- The 2023 study reported detection of one or more PBDEs in each breast-milk sample analyzed (Schreder et al. 2023).
- The study also detected bromophenols and selected replacement flame retardants, indicating potential exposure to nursing infants through breast milk (Schreder et al. 2023).
- Other studies have reported associations or concerns involving thyroid-related endpoints for selected flame retardants; those findings should not be interpreted as health outcomes demonstrated by the breast-milk study itself (Leonetti et al. 2016).

Environmental and Regulatory Observations

- PBDE concentrations in North American breast milk have declined significantly following phaseouts and other market or regulatory changes. The observed decline is consistent with reduced exposure to certain legacy PBDEs, although the cited study does not necessarily isolate the effect of any single intervention (Guo et al. 2016).
- Replacement flame retardants and bromophenols continue to be detected, raising questions about whether replacement chemicals were sufficiently characterized before broader use and whether safer alternatives were fully evaluated (Schreder et al. 2023).

Broader Considerations

- The example illustrates how hazard, exposure, performance, and life-cycle information may inform product design, substitution, and regulatory decisions.
- The continued detection of legacy PBDEs illustrates that exposure may continue after production or use has been phased out because products remain in service and chemicals may persist in indoor or environmental media.

Relevance to Sustainable Systems

This case study illustrates how chemical-selection decisions can have implications across product design, manufacturing, use, and end-of-life management. The continued detection of phased-out PBDEs and selected replacement flame retardants in breast milk indicates that exposures can persist or emerge after market and regulatory changes. Considering hazard, exposure potential, performance requirements, and life-cycle implications when comparing alternatives may help identify potential tradeoffs and reduce the likelihood of regrettable substitution. The findings are specific to the chemicals, samples, methods, and sources evaluated and do not establish that all BFRs or all potential alternatives have the same hazard or exposure profile.

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Product Design Case Study: Cellulose-Based Plastic and Microplastic Formation

Purpose and Objective

This case study examines how green and sustainable chemistry considerations may be incorporated into material design to address end-of-life behavior. It describes an emerging cellulose-based supramolecular plastic designed to disassemble in sufficiently saline environments rather than form persistent microplastic particles and identifies considerations and data gaps relevant to evaluating its potential applications, environmental fate, recovery, and scalability.

Overview

Researchers at the RIKEN Center for Emergent Matter Science developed a cellulose-based supramolecular plastic designed to reduce microplastic formation. The material is formed from carboxymethyl cellulose (CMC), a cellulose-derived polymer, and a guanidinium-functionalized component produced from low-molecular-weight branched polyethyleneimine (PEI). The negatively charged CMC chains and positively charged PEI-derived guanidinium groups form reversible ionic interactions that create the material's supramolecular network. Choline chloride can be added as a plasticizer to increase flexibility and reduce brittleness (Chen et al. 2025).

This material represents an emerging approach to designing end-of-life behavior directly into a material's molecular structure. Unlike some conventional plastics that can persist and fragment following release or disposal, the supramolecular network is designed so that its ionic interactions can be disrupted under sufficiently saline conditions. Disassembly does not eliminate the material's chemical constituents, making constituent hazards, sourcing, and environmental fate important considerations in evaluating its overall sustainability.

Problem

Conventional plastics can fragment into persistent microplastics during environmental degradation and have been detected in environmental media, food-related pathways, and human tissues. Designing alternatives that reduce persistent fragmentation could help address this problem. Substituting one material for another, however, can introduce different environmental or chemical hazards that must also be considered.

Material-Design Approach

The material uses reversible ionic interactions as an end-of-life design mechanism. Negatively charged CMC chains interact with positively charged PEI-derived guanidinium groups to maintain the polymer network during use. Under sufficiently saline conditions, salts disrupt these interactions, allowing the network to disassemble rather than persistently fragment into microplastic particles. The same salt-responsive behavior was also evaluated under controlled conditions to separate and potentially recover constituent materials.

End-of-Life Management Pathway

- **Input:** Single-use and short-lived products fabricated from CMC supramolecular plastic (CMCSP) could potentially include films, packaging, and lightweight consumer items, subject to application-specific performance and safety evaluation. At end of life, these products could enter conventional

waste-management systems or, if improperly disposed of or lost during use, enter coastal or marine environments.

- **Process:** Upon exposure to sufficiently saline conditions, the material undergoes molecular disassembly rather than persistent fragmentation. The material's structure is maintained by reversible ionic "salt bridge" interactions between negatively charged CMC chains and positively charged PEI-derived guanidinium groups. Salts disrupt these ionic interactions, causing the polymer network to disassemble into its constituent components. The study reported dissociation of uncoated CMCSP in artificial seawater within 48 hours and demonstrated controlled disassembly using a salt solution as part of a laboratory-scale recovery process.
- **Output:** Disassembly reduces the potential for formation of persistent microplastic particles but does not eliminate the material's chemical constituents. If disassembly occurs in the environment, the constituent materials disperse into the surrounding water where their environmental fate and potential ecological effects would require further evaluation. Under controlled conditions, the study demonstrated that CMC and the PEI-derived component could be separated and recovered for potential reuse.

Material Loop

The material provides two potential end-of-life pathways. If the material enters seawater or another sufficiently saline environment, its ionic network can disassemble, reducing the potential for persistent microplastic formation. This environmental disassembly does not represent a closed material loop because the constituent materials disperse into the surrounding water rather than being captured for reuse, and their environmental fate requires further evaluation. Alternatively, the study demonstrated a controlled, laboratory-scale recovery process in which salt-induced disassembly was followed by separation and recovery of CMC and the PEI-derived component for potential reuse. This managed pathway indicates the potential for controlled material recovery, although reuse in newly manufactured material and feasibility at commercial scale have not yet been established.

Outcome and Potential Impacts

- **End-of-Life Behavior:** The study reported dissociation of uncoated CMCSP under the sufficiently saline laboratory conditions evaluated, including artificial seawater and controlled salt solutions, reducing the potential for persistent microplastic formation under those conditions. Dissociation prevents persistence as intact plastic particles but does not mean the material's chemical constituents disappear from the environment.
- **Material Performance:** The study reported strength, transparency, and flexibility that the researchers compared with selected conventional plastics under the tested conditions.
- **Material Efficiency:** The study evaluated thin films of approximately 0.07 mm. Whether this thickness produces a material-efficiency advantage depends on the application and performance comparison.
- **Feedstock and Hazard Considerations:** The method incorporates renewable CMC but also includes a PEI-derived constituent that should be considered when evaluating the material's overall hazard and sustainability profile.
- **Environmental Safety and Chemical Considerations:** Although the study included laboratory toxicity testing, dissociation of the material in saline solutions results in its constituent materials being released into the surrounding water. The study did not evaluate marine bioaccumulation, chronic aquatic toxicity, or the environmental effects of intentional disposal of the material or its dissociated constituents in marine environments. A complete understanding of material composition and additional independent environmental testing would be needed to evaluate the toxicity, persistence, bioaccumulation potential, and ecological effects of the dissociated constituents and inform evaluation of suitability for specific applications or potential release scenarios. For applications

involving environmental release, broader considerations would also include potential regulatory and liability implications, conditions defining where and when the material may be appropriately used, and whether avoidance or mitigation measures are needed to limit exposure or unintended environmental effects.

- **Recovery and Reuse Potential:** The method demonstrates potential for controlled salt-based disassembly and recovery of constituent materials, indicating a potential managed end-of-life pathway that could use a controlled salt solution without relying on access to seawater.
- **Energy and Cost Considerations:** Energy and cost advantages relative to conventional petroleum-based plastics have not yet been established. Although the material incorporates cellulose-derived CMC, production of CMC and the other constituents require chemical and energy inputs, while conventional plastics benefit from mature, large-scale manufacturing infrastructure and economies of scale. This study did not conduct a comparative life-cycle or commercial-scale cost assessment.
- **Scale-Up and Market Adoption:** The material has been demonstrated at the research scale but has not yet been demonstrated through commercial-scale manufacturing or market adoption. Therefore, this case study should be viewed as an example of an emerging material-design approach rather than a commercially proven alternative. Transitioning from laboratory development to widespread use would require evaluation of manufacturing scalability, production costs, consistent material performance, supply chains, regulatory requirements, and application-specific performance and safety. These considerations may affect the material's ability to compete with established petroleum-based plastics.
- **Performance Limitations:** Material properties are affected by moisture and salinity. The study demonstrated water uptake under high-humidity conditions and changes in mechanical properties as water content increased. In separate testing, uncoated CMCSP swelled but did not dissociate in deionized water, whereas it dissociated in artificial seawater within 48 hours. The study did not evaluate prolonged contact with water, aqueous products, or salty foods or establish a commercial shelf life. Therefore, these conditions would require further evaluation for potential packaging applications. For specific applications, additional performance considerations may include defining salinity and temperature thresholds for dissociation and evaluating structural integrity under different exposure conditions, such as high humidity, marine fog, salt spray, and full seawater submersion. These technical parameters would require application-specific testing and are beyond the scope of this general case study.
- **Potential Applications:** The material may have potential applications in packaging, consumer products, and expendable maritime components or protective housings where controlled end-of-life disassembly could reduce persistent plastic waste. Suitability for specific applications, particularly those involving intentional release into marine environments, would require consideration of material performance, constituent hazards, environmental exposure, applicable regulatory requirements, and end-of-life conditions.

Relevant Green and Sustainable Chemistry Considerations

- **Prevention:** The material is designed to reduce the potential for persistent microplastic formation under sufficiently saline conditions by disassembling rather than persistently fragmenting.
- **Design for Disassembly:** Reversible ionic interactions enable the polymer network to disassemble under sufficiently saline conditions, including artificial seawater and controlled salt conditions evaluated in the study.
- **Alternative Chemistry Considerations:** Incorporates renewable, cellulose-derived CMC. The material also contains a PEI-derived constituent, highlighting the need to consider constituent hazards and environmental fate alongside improved end-of-life performance.

- **Use of Renewable Feedstocks:** The method relies in part on cellulose-derived CMC, providing a renewable component. The specific source of the cellulose used in the study is not identified, and not all constituents are renewable. Further evaluation of feedstock sourcing and the energy and chemical inputs required to produce CMC and the other material constituents would be needed to assess life-cycle benefits compared with conventional petroleum-based products.
- **Disassembly Conditions:** The study reported disassembly under ambient laboratory conditions in sufficiently saline solutions without elevated temperatures or industrial composting. The energy requirements of a managed recovery process were not evaluated at commercial scale.
- **Circular Economy:**
    - **Environmental Disassembly:** If the plastic enters seawater or another saline environment, its ionic bonds break apart, and the material's constituents disperse into the surrounding water. The microplastic may be gone, but the chemical constituents (including the PEI-derived component) are still present in the environment. They are not being captured and reused.
    - **Controlled Material Recovery:** The material is intentionally treated with a salt solution in a managed process. The CMC and PEI-derived components are then separated, recovered, and potentially reused to manufacture new material.

Relevance to End-of-Life Management of Advanced Materials

This case study examines an emerging approach to advanced material design in which end-of-life behavior is incorporated into the material's molecular architecture. By enabling dissociation under sufficiently saline conditions rather than persistent fragmentation, the CMCSP system has the potential to reduce the formation of persistent microplastics. The study indicates that a material can be designed to retain selected useful properties during the tested use conditions while also providing a controlled pathway for disassembly and potential constituent recovery. The material remains at the research stage, and further evaluation of constituent hazards, environmental fate, application-specific performance, manufacturing scalability, cost, and realistic end-of-life conditions would be needed before commercial-scale adoption.

Reference

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Product Design Case Study: Regrettable Substitution in Selected "BPA-Free" Products

Purpose and Objective

This case study examines the potential for regrettable substitution when bisphenol A (BPA) is replaced with structurally related chemicals that may have comparable or insufficiently characterized hazards. It considers how hazard, exposure, performance, environmental fate, and life-cycle information may inform evaluation of BPA alternatives. Alternatives assessment and class-based evaluation may help identify whether a substitution reduces hazards or shifts concerns to another chemical.

Overview

This case study examines product design decisions in which BPA was replaced with structurally related bisphenols while maintaining product performance and compatibility with existing applications. Green and sustainable chemistry considerations during product design may include alternatives assessment, hazard and exposure evaluation, life-cycle thinking, performance, and end-of-life implications.

Reviews of BPA alternatives have identified structurally related compounds, including bisphenol S (BPS), bisphenol F (BPF), bisphenol AF, and bisphenol Z, in various products and environmental media. BPS and BPF, for example, have been used as BPA alternatives in applications such as thermal paper, plastics, resins, and coatings. These compounds may preserve functional characteristics associated with BPA, but available information indicates that their hazard, exposure, persistence, bioaccumulation, and environmental-transport profiles vary (Adamovsky et al. 2024; Maertens et al. 2021). Although these substitutions preserved functional performance and compatibility with existing manufacturing systems, the substitutions did not necessarily eliminate the hazard concerns associated with the broader bisphenol class and introduced additional uncertainty regarding environmental fate, toxicity, and exposure pathways. This illustrates how early material-selection decisions may affect potential hazards, exposures, and management considerations during product use, recycling, disposal, and environmental release.

Some BPA substitutions appear to have relied primarily on removing BPA while retaining structurally related bisphenols, sometimes with limited hazard, exposure, and life-cycle information for the replacement chemicals. Many of the reviewed alternatives retained phenolic structural features associated with biological activity. Follow-up studies evaluated these product design choices using a weight-of-evidence approach combined with physicochemical property analysis (e.g., hydrophobicity, ionization state, and chemical stability). Environmental monitoring data documented the presence of BPA alternatives in water, sediments, biota, and consumer products. Together, these information sources help characterize how chemical-selection decisions may influence environmental occurrence, potential exposure, and biological activity.

The reviewed studies indicate that several BPA alternatives retain phenolic features associated with endocrine activity and may exhibit baseline or specific toxicities comparable to or greater than BPA. The alternatives also vary in persistence, bioaccumulation potential, and environmental transport. These findings illustrate why substitution with a structurally related bisphenol should not be assumed to produce a more favorable hazard or exposure profile and why some substitutions may be characterized as regrettable.

Problem

Replacing BPA with a structurally related bisphenol may retain endocrine or other toxicological concerns. A “BPA-free” claim communicates the absence of BPA but does not, by itself, characterize the hazards or potential exposures associated with the replacement chemical.

Alternative Design and Evaluation Approaches

Some BPA-free reformulations use structurally related bisphenols that retain phenolic features associated with endocrine activity. Such substitutions may shift rather than resolve hazard concerns and may introduce additional uncertainty regarding exposure and environmental fate (Adamovsky et al. 2024; Maertens et al. 2021). Thermal paper provides one example in which alternatives may include chemical substitutions and functional or system-level changes. Potential approaches include non-bisphenol color-development systems, reducing or eliminating unnecessary printed receipts, and electronic receipt options. Evaluation of these alternatives may consider hazard, exposure potential, performance, technical feasibility, cost, and life-cycle implications (MN PCA 2026; USEPA OCSPP 2014). These approaches illustrate how alternatives assessment can extend beyond one-to-one chemical substitution to consider changes in chemistry, material design, or delivery of the required function

Life-Cycle Pathway: Product Design

- **Input:** Selected consumer and industrial products marketed as BPA-free that use alternative bisphenols in plastics, resins, coatings, or other applications.
- **Process:** Depending on the chemical, product, use, and management pathway, alternative bisphenols may migrate or be released during use, weathering, recycling, treatment, or disposal. The chemicals may subsequently enter wastewater, surface water, sediment, soil, or secondary-material streams. The ability of water-treatment and recycling systems to identify, remove, or manage these compounds varies by chemical, process, and facility.
- **Output:** Environmental occurrence of multiple bisphenol analogues, some of which have demonstrated biological activity, can complicate monitoring, exposure assessment, and management.

Material Loop and Circularity Assessment

Many BPA alternatives were selected for their function in products rather than specifically for degradation, chemical recovery, or removal during recycling. Depending on the material and recycling process, bisphenol analogues may remain in or enter secondary material streams. This illustrates why chemical content and potential downstream exposures may be relevant when evaluating circularity.

Outcomes and Potential Impacts

- **Reviewed BPA alternatives vary substantially in hydrophobicity and toxicity-related properties.** Hydrophobicity refers to how strongly a chemical tends to associate with fats, oils, and biological tissues rather than water. Greater hydrophobicity can contribute to bioaccumulation potential, although actual environmental fate and bioaccumulation also depend on factors such as ionization, metabolism, degradation, and exposure condition. Studies evaluating BPA alternatives found substantial variation in hydrophobicity, chemical stability, and toxicity across substitute compounds, meaning some alternatives may more readily move through water systems while others may accumulate in sediments, wildlife, or human tissues. Toxicity potential also varied considerably, with several BPA substitutes demonstrating endocrine-disrupting activity, cytotoxicity, or environmental persistence comparable or greater than BPA itself. This variability complicates environmental fate

prediction, exposure assessment, regulatory evaluation, and safer product design because replacement chemicals may introduce different but equally significant human health and environmental risks.

- **Some laboratory studies reported cytotoxicity for selected BPA alternatives at concentrations comparable to or lower than those associated with BPA.**
  Laboratory studies show that some BPA replacements damage or kill cells at concentrations similar to, or lower than, those required for BPA, indicating that substitution does not necessarily reduce biological harm.
- **Retention of certain phenolic structural features may contribute to endocrine activity.**
  Systematic reviews have reported hormonal activity for BPS and BPF, although potency, endpoints, and findings vary among studies (Rochester and Bolden 2015).
- **Predictive toxicology tools are limited by sparse and inconsistent data.**
  Computer-based toxicity predictions depend partly on the availability, quality, and relevance of experimental data. This variability reduces confidence in toxicity predictions and increases uncertainty in risk assessment.
- **Substitution with multiple structurally related chemicals may increase monitoring and regulatory complexity, particularly when hazard and exposure information is incomplete.**
  Such substitution does not necessarily reduce the hazard associated with the original function or chemical class.

Relevant Green and Sustainable Chemistry Considerations

- **Hazard Reduction:** Substitution with a structurally related bisphenol may retain some of the original hazard concerns.
- **Exposure Considerations:** Persistence, migration, bioaccumulation, and exposure pathways vary among alternatives and may be incompletely characterized.
- **Use of Available Information:** Hazard, exposure, performance, and end-of-life information may be incomplete or uneven across potential alternatives.
- **Comparison of Alternatives:** Chemical substitutes, material changes, product redesign, and functional alternatives may warrant evaluation rather than assuming that a “BPA-free” product has a more favorable profile.

Relevance to Product Design and Life-Cycle Decision-Making

This case study illustrates how chemical-selection decisions made during product design may affect hazard, exposure, manufacturing compatibility, product use, recycling, disposal, and environmental release. Reviews of BPA alternatives indicate that some structurally related substitutes retain endocrine or other toxicological concerns and that data availability varies among chemicals. The example also illustrates why “free-of” claims should not be interpreted as complete comparisons of hazard or exposure profiles. Alternatives assessment can support comparison of chemical substitutes, material changes, product redesign, and functional alternatives while considering performance and life-cycle tradeoffs. The findings apply to the chemicals and studies evaluated and do not establish that every BPA-free product or every non-bisphenol alternative has the same hazard or exposure profile.

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Product Design Case Study: Fiber-Based Alternatives to Selected Single-Use Plastics

Purpose and Objective

This case study examines how green and sustainable chemistry considerations may be incorporated into product design through the selection of agricultural fiber feedstocks and molded-fiber manufacturing. It describes tableware made from sugarcane bagasse and bamboo and considers material composition, chemical additives, functional performance, manufacturing, and potential end-of-life pathways. The example also identifies conditions and limitations relevant to evaluating biodegradation, composting, life-cycle impacts, and commercial application.

Overview

Single-use plastic food containers can contribute to persistent waste and may contain additives that affect potential exposures and downstream material management. Researchers have evaluated molded-fiber tableware composed primarily of sugarcane bagasse, the fibrous cellulose-rich residue remaining after sugarcane juice extraction, and bamboo fibers (Liu et al. 2020). The study examined whether this fiber-based formulation could provide selected food-contact performance without using a conventional plastic polymer as the primary structural material. This case study considers the manufacturing pathway, functional performance, chemical additives, and end-of-life characteristics reported for the tableware.

Problem

Conventional single-use food containers may use persistent plastic polymers and intentionally added substances such as plasticizers, antioxidants, colorants, processing aids, or barrier treatments. Depending on the polymer, additive, product use, and management pathway, chemicals may migrate during use or enter waste, recycling, treatment, or environmental streams after disposal. Persistent materials and additives can therefore affect potential exposures and end-of-life management.

Material Design Approach

Rather than modifying a conventional plastic formulation, the approach evaluated by Liu et al. uses sugarcane bagasse and bamboo fibers as the primary structural materials. Functional performance is provided through fiber composition, molded-pulp processing, and the use of a sizing agent to improve water and oil resistance. The study reported biodegradation and composting characteristics under specified test conditions and compared selected manufacturing impacts and costs with other tableware materials (Liu et al. 2020).

Life-Cycle Pathway: Product Design

- **Input:** Sugarcane bagasse and bamboo fibers used as feedstocks for the molded-fiber formulation evaluated in the study.
- **Process:** Bagasse and bamboo fibers are mechanically pulped, combined into a fiber slurry, and molded under heat and pressure into tableware. Alkyl ketene dimer is used as a sizing agent to improve water and oil resistance (Lindström and Larsson 2008; Liu et al. 2020).
- **Output:** Single-use cups, plates, and containers for which the study evaluated mechanical and food-contact performance, biodegradation, composting, manufacturing impacts, and cost. Performance and end-of-life results depend on the formulation and test conditions evaluated.

Material Loop and Circularity Assessment

The fiber-based tableware is intended to biodegrade or compost under suitable conditions rather than persist as an intact plastic product. Liu et al.(2020) reported visible decomposition in soil beginning within approximately 30 to 45 days and loss of structural integrity within approximately 60 days under the conditions evaluated. These findings do not establish the same degradation rate in landfills, aquatic environments, home-composting systems, industrial composting facilities, or other settings. Actual end-of-life outcomes depend on temperature, moisture, microbial activity, product composition, coatings or additives, collection systems, and available composting or waste-management infrastructure. This supports circularity goals by aligning material performance with potential compatibility with specified biological end-of-life pathways.

Outcome and Potential Impacts

- **Conventional Plastic Polymer Use:** The formulation evaluated in the study used molded agricultural fibers rather than a conventional petroleum-based plastic polymer as its primary structural material. Chemical additives, including a sizing agent, remained part of the material system.
- **End-of-Life Characteristics:** The study reported biodegradation and composting under specified conditions. Whether the product would degrade under actual disposal conditions depends on the receiving environment and available collection and waste-management systems.
- **Manufacturing and Life-Cycle Comparisons:** The study reported lower selected manufacturing impacts for the evaluated fiber-based tableware than for the comparison products included in its analysis. The result depends on the system boundary, feedstock assumptions, manufacturing data, impact categories, and comparator products used.
- **Resource Use:** The use of sugarcane bagasse may provide an additional application for an agricultural processing residue. The implications depend on existing uses of the feedstock, transportation, processing requirements, availability, and competing demands. Bamboo is renewable but should be evaluated separately from bagasse because it is not necessarily a waste or residual feedstock.
- **Cost and Adoption Considerations:** The study reported estimated production costs comparable to polystyrene cups and lower than selected biodegradable-polymer alternatives. Broader applicability may depend on feedstock availability and consistency, product specifications, manufacturing capacity, performance requirements, certification, disposal conditions, infrastructure, and market acceptance.

Relevant Green and Sustainable Chemistry Considerations

- **Prevention and Material Substitution:** The approach replaces a conventional plastic structural material with a molded-fiber formulation. Evaluation should also consider the sizing agent and other processing or performance additives.
- **Material and Chemical Selection:** Bagasse and bamboo provide the primary fiber structure, while alkyl ketene dimer contributes water and oil resistance. The complete formulation, potential migration, and hazard profiles of additives remain relevant.
- **Design for Biological End-of-Life Pathways:** The product was evaluated for biodegradation and composting under specified conditions. Degradation rates and products may differ under actual disposal conditions.
- **Life-Cycle Thinking:** Feedstock sourcing, manufacturing, product performance, transportation, use, collection, composting, degradation, and disposal may all affect the comparison with conventional products.

- **Circularity Considerations:** Biological recovery may be possible where the material is suitable and collection and composting systems are available. Renewable content or biodegradability alone does not establish circularity or environmental preference.

Relevance to Product Design and End-of-Life Management

This case study examines how material selection and product design may influence manufacturing, functional performance, and end-of-life pathways. The molded-fiber formulation uses sugarcane bagasse and bamboo as primary structural materials and was evaluated for food-contact performance, biodegradation, composting, selected manufacturing impacts, and cost. The example illustrates the importance of evaluating the complete material formulation, including additives, and of identifying the conditions and infrastructure required for intended end-of-life pathways. The reported findings are specific to the formulation, test methods, comparison products, and environmental conditions evaluated and do not establish that every fiber-based product is safer, compostable, or environmentally preferable to every plastic alternative.

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Product Design Case Study: Alternative Thermal-Paper Imaging Technology

Purpose and Objective

This case study examines the application of green and sustainable chemistry considerations to the design of an alternative thermal-paper imaging system. It describes an alternative thermal imaging technology intended to eliminate the need for bisphenol A (BPA)- and bisphenol S (BPS)-based chemical developers while maintaining compatibility with existing thermal printing infrastructure. The case study also considers potential human-health and environmental implications, implementation considerations, and remaining data gaps and tradeoffs associated with the alternative technology.

Overview

Conventional thermal paper used for receipts and labels commonly uses a heat-sensitive coating containing a color developer. BPA has historically been used as a developer in some thermal-paper formulations where it reacts with a dye when heat is applied to produce a visible image. BPA has been identified as a chemical of concern because of its potential to interfere with hormone signaling (Cimmino et al. 2020).

Dow Chemical Company, in partnership with Koehler Paper Group, developed ROPAQUE™ Ultra EF, a voided-polymer technology for thermal printing. The technology uses hollow-sphere polymeric pigments that create an image through a physical change: heat from the print head collapses air-filled voids, causing the spheres to become transparent and reveal a colored layer beneath. This mechanism avoids the use of a chemically reactive BPA- or BPS-based developer in the thermal imaging system (USEPA OCSPP 2017).

Problem

Some conventional thermal-paper formulations use BPA, BPS, or other chemical developers. BPA and certain alternative developers have raised human-health or environmental concerns, and handling thermal paper can create opportunities for dermal exposure to developers that are present in an unbound form.

Alternative Design Approach

Dow developed an ammonia-free hollow-sphere polymeric pigment for use in thermal-paper coating. In the receipt-paper application described by the U.S. Environmental Protection Agency (USEPA), microscopic air-filled spheres obscure a colored base layer. When heat is applied by a thermal print head, the spheres collapse and become transparent, revealing the color beneath and producing an image without a BPA- or BPS-based chemical developer (USEPA OCSPP 2017).

Life-Cycle Pathway: Product Design

- **Input:** Some conventional thermal-paper formulations use a paper substrate, a colored base layer, and a heat-sensitive coating containing a chemical developer such as BPA or BPS. The alternative design replaces the developer system with an ammonia-free coating containing hollow-sphere polymeric pigments that obscure the colored layer until printing.
- **Process (Life-Cycle Stage):** During product design and manufacture, the physical imaging mechanism is incorporated into thermal paper as an alternative to chemically reactive developers. When a thermal print head applies heat, the hollow polymer spheres collapse and become transparent, revealing the colored layer beneath and creating the printed image. The technology is

designed to function with existing thermal printing equipment, which may reduce the need for changes to printers or point-of-sale infrastructure.

- **Output:** The resulting receipt paper produces a thermal image without BPA- or BPS-based chemical developers. This design avoids potential dermal exposure to BPA or BPS from the thermal developer, although evaluation of the full formulation would be needed to characterize other potential exposures. This may limit the introduction of bisphenol developers into paper recycling and disposal streams while maintaining the intended printing function.
- **Material Loop and End-of-Life Considerations:** Eliminating BPA and BPS developers may reduce contamination of recycled paper with these chemicals of concern. The polymeric hollow-sphere pigments remain with the paper after use, and the available information does not establish their behavior during recycling, disposal, degradation, or environmental release. A complete life-cycle assessment would require additional information on polymer composition, recyclability, degradation products, and the potential for particle release.

Outcomes and Potential Impacts

- **Implementation Considerations:** The technology is designed as a drop-in replacement compatible with existing thermal printing infrastructure, which may facilitate adoption by reducing the need for equipment modifications or replacement and associated implementation costs.
- **Potential Reduction in Bisphenol Exposure:** The alternative imaging system is intended to avoid BPA and BPS developers, thereby removing a potential source of dermal exposure to those chemicals during receipt handling. Studies have reported transfer of BPA from thermal receipt paper to skin and elevated BPA exposure among cashiers who routinely handled BPA-containing thermal paper (Biedermann et al. 2010; Ndaw et al. 2016) Actual exposure implications of the alternative would depend on the complete coating formulation, use conditions, and potential migration or release of replacement materials.
- **Formulation Considerations:** The ammonia-free formulation uses sodium hydroxide rather than ammonia as the neutralizer and has been described by the manufacturer as having a low-odor profile and being suitable for low volatile organic compound (VOC) waterborne coating formulations (Dow Chemical Company 2021). Available data do not establish a direct quantitative reduction in total VOC emissions from the thermal-paper application itself.
- **Performance Considerations:** The physical imaging mechanism may offer different performance characteristics than conventional chemically developed thermal paper. Image durability under conditions such as elevated temperatures, sunlight, moisture, and chemical exposure may be important when evaluating the technology for specific applications. Comparative performance under these conditions was not evaluated in the sources reviewed for this case study.
- **End-of-Life Considerations:** The alternative technology eliminates the need for BPA or BPS chemical developers in the thermal imaging process, which may reduce the introduction of these chemicals into the paper waste stream. The imaging technology, however, relies on polymeric hollow-sphere pigments that remain associated with the paper after use. The available information reviewed for this case study does not provide sufficient data to characterize the toxicity, persistence, degradation products, or environmental fate of these polymers during paper use, wear, recycling, degradation, treatment, or disposal, including whether the polymers could be released as or contribute to microplastic particles. Therefore, while the technology eliminates known chemical developers such as BPA and BPS, the available information is insufficient to conclude that the polymeric alternative is without potential human-health or environmental risks throughout its life cycle. Additional information on polymer composition, potential releases and degradation products, potential microplastic formation, recyclability, and human and ecological hazards would be needed to fully evaluate these potential risks and tradeoffs.

Relevant Green and Sustainable Chemistry Considerations

- **Chemical and Material Selection:** The technology avoids BPA- and BPS-based developers by replacing the chemically reactive developer system with a physical imaging mechanism. The available information does not fully characterize the hazard, exposure, or environmental-fate profiles of the polymeric pigments or other formulation components.
- **Process and Formulation Inputs:** The formulation is ammonia-free and uses sodium hydroxide rather than ammonia as the neutralizer. The manufacturer reports a low-odor profile and suitability for low-VOC waterborne coating formulations (Dow Chemical Company 2021). Comparative information on the full manufacturing process and emissions was not available in the sources reviewed.

Relevance to Sustainable Systems

This case study examines a design change that replaces a chemically reactive bisphenol-based developer system with a physical imaging mechanism. The example illustrates how functional or system-level alternatives may differ from one-to-one chemical substitution. Avoiding BPA and BPS developers may alter potential exposures and the chemical content of paper recycling or disposal streams while introducing different material and end-of-life considerations associated with the polymeric pigments. Evaluation of the complete alternative would therefore require information about performance, full formulation, potential releases, recycling compatibility, degradation products, and environmental fate. The available information does not establish that the alternative is preferable across every human-health, environmental, performance, or life-cycle attribute.

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Production and Manufacturing Case Study: Renewable and Waste-Derived Biopolymers for Water Treatment, Agriculture, and Material Applications

Purpose and Objective

This case study examines how green and sustainable chemistry (GSC) considerations may be incorporated into the production and use of renewable or waste-derived biopolymers. It describes selected applications of chitosan, alginate, and cellulose chemistries in water treatment, agriculture, and material or consumer-product applications. The case study considers reported performance, feedstock and manufacturing characteristics, potential resource and waste implications, and factors relevant to scaling and implementation. It also identifies life-cycle, toxicity, degradation-product, economic, and data considerations that may need to be evaluated before conclusions are drawn about broader adoption.

Overview

Biopolymers and renewable or secondary feedstocks are being evaluated for applications in water treatment, agriculture, packaging, and other material systems. Examples include chitosan derived from crustacean-shell material, alginate derived from algae, and cellulose derived from plant-based feedstocks. Peer-reviewed literature has examined chitosan-based flocculants and cellulose-, chitosan-, and other biomaterial-based membranes for water treatment, while companies report commercial or developing applications in agriculture, packaging, and consumer products (Lustenberger and Castro-Muñoz 2022; Mycodev Group 2026; Tidal Vision 2026; Yang et al. 2016). These examples involve GSC considerations such as feedstock selection, pollution prevention, material performance, biodegradability, resource use, and end-of-life management. The relevance and outcomes of these considerations vary by polymer, formulation, application, and management pathway.

Problem

Chemicals and materials used in water treatment, agriculture, and manufacturing differ in hazard, persistence, resource requirements, performance, and end-of-life characteristics. Some applications may involve hazardous inputs, persistent materials, energy- or resource-intensive processing, or wastes requiring management. These considerations have contributed to interest in renewable and waste-derived biopolymer alternatives.

Biopolymer Approaches

Organizations and researchers are developing biopolymer chemistries from renewable or secondary feedstocks for a variety of applications. Tidal Vision reports applications of chitosan derived from crustacean-shell material, and CuanTec and Mycodev Group describe chitosan or related biopolymer applications in packaging, agriculture, or other commercial markets. Peer-reviewed literature also evaluates chitosan-based flocculants and cellulose-, chitosan-, and other biomaterial-based membranes for water treatment. Claims concerning waste reduction, performance, scale, cost, or environmental benefits should be interpreted according to the evidence, formulation, application, and comparison used (Lustenberger and Castro-Muñoz 2022; Mycodev Group 2026; Tidal Vision 2026; Yang et al. 2016).

Life-Cycle Pathway: Production and Manufacturing

- **Input:** Potential feedstocks include crustacean-shell material from seafood processing, algae-derived materials used to produce alginate, and plant-based feedstocks used to produce cellulose. The

designation of a material as a waste, byproduct, or renewable feedstock depends on its source, existing uses, processing requirements, and applicable market.

- **Process:** Feedstocks undergo extraction, purification, and, depending on the application, chemical modification or fabrication to produce chitosan, alginate, cellulose derivatives, flocculants, membranes, sorbents, or other materials. Process inputs, yields, solvents, reagents, energy and water requirements, emissions, and residuals vary by technology. Some commercial developers describe their processes as waste-reducing or zero-waste, but those claims depend on the system boundary and supporting data.
- **Output:** Potential outputs include chitosan-, alginate-, and cellulose-based flocculants, membranes, sorbents, agricultural products, packaging materials, and formulation ingredients. Their performance, biodegradability, hazard profile, environmental fate, and potential to replace an incumbent chemistry depend on the polymer, molecular modification, additives, application, and conditions of use and disposal.

Outcomes and Potential Impacts

- **Water-Treatment Performance and Applicability:** Chitosan-based flocculants can be modified for removal of suspended colloids and selected dissolved pollutants. Reviews of cellulose-, chitosan-, and other biomaterial-based membranes also report removal of dyes, metals, salts, microorganisms, oils, and other contaminants under varied experimental conditions. Reported examples include dye or organic-pollutant rejection of 96.7 percent to 98.8 percent, copper and hexavalent chromium removal above 91 percent, and complete removal of iron and aluminum under the particular acid-mine-water conditions reviewed. These results should not be interpreted as performance guarantees across other contaminants, water matrices, operating conditions, or scales (Lustenberger and Castro-Muñoz 2022; Yang et al. 2016).
- **Potential Pollution Prevention and Treatment Considerations:** Replacing an incumbent treatment chemical with a biopolymer may reduce reliance on a persistent or more hazardous substance in some applications, but that conclusion requires comparison of the specific chemicals, formulations, doses, performance, process inputs, and residuals. Chitosan is generally described as biodegradable and can be chemically modified for different treatment functions. Modification, however, may change toxicity, biodegradability, environmental fate, and treatment-residual characteristics (Yang et al. 2016).
- **Secondary Feedstocks and Resource Use:** Crustacean shells and selected agricultural or processing residues may serve as feedstocks for chitosan, cellulose, or related materials. Some reviewed water-treatment technologies also incorporate non-biopolymer secondary materials, such as eggshell-derived materials, oil-palm residues, or fly ash. Use of a secondary material may divert a waste stream or reduce demand for a virgin input, but the net implications depend on collection, transportation, preprocessing, purification, existing uses, contaminants, yields, and competing demands (Lustenberger and Castro-Muñoz 2022).
- **Scale and Market Potential:** Company materials report applications of biopolymer chemistries in water treatment, agriculture, packaging, and consumer-product markets, along with potential reductions in conventional chemical use, fertilizer demand, treatment costs, or hazardous-material use. These claims illustrate potential applications and commercial interest but should be distinguished from independently verified comparative performance, cost, hazard, or life-cycle findings.
- **Implementation Considerations and Data Gaps:** Broader application may depend on feedstock quality and variability, contaminant-specific performance, dose, regeneration or reuse, mechanical durability, product consistency, manufacturing capacity, cost, and access to extraction or fabrication technologies. Comparative life-cycle, hazard, exposure, toxicity, degradation-product, residual-management, and economic assessments may be needed to evaluate net benefits and potential

unintended impacts, particularly when biopolymers are chemically modified or combined with nanomaterials, cross-linkers, or specialized solvents (Lustenberger and Castro-Muñoz 2022; Yang et al. 2016).

Relevant Green and Sustainable Chemistry Considerations

- **Pollution Prevention:** In some applications, biopolymers may replace an incumbent chemical or material with different hazard, persistence, resource, or waste characteristics. The implications require comparison of the specific alternatives and application.
- **Hazard and Exposure Considerations:** Chitosan, alginate, cellulose, and their modified forms can differ in molecular weight, charge, additives, toxicity, biodegradability, and environmental fate. The complete formulation and intended use should be considered rather than assuming that a biopolymer is inherently safer because it is biobased**.**
- **Handling and Process Considerations: C**hanges in chemical inputs may alter occupational hazards associated with storage, handling, transport, and processing. Comparative information is needed to determine whether a biopolymer formulation reduces or introduces particular workplace hazards.
- **Renewable and Secondary Feedstocks:** Crustacean-shell material and selected plant or algae feedstocks may provide renewable or secondary inputs for biopolymer production. Their resource implications depend on sourcing, existing uses, transportation, extraction, purification, and yield.
- **Circularity Considerations:** Use of processing residues as feedstocks may retain material value and reduce disposal in some systems. Circularity depends on the complete production process, coproducts and residuals, product lifetime, recovery or degradation pathway, and available infrastructure.

Relevance to Sustainable Systems

This case study examines renewable and waste-derived biopolymer chemistries used or proposed for water treatment, agriculture, packaging, and other material applications. Peer-reviewed studies report contaminant-removal performance for selected chitosan-based flocculants and biomaterial-based membranes under specified conditions, while company sources describe additional commercial applications. The example illustrates how feedstock selection, chemical modification, manufacturing, functional performance, residual management, and end-of-life behavior may influence evaluation of a biopolymer alternative. Findings should be interpreted according to the particular polymer, formulation, application, test conditions, comparator, scale, and source. Biobased or biodegradable content alone does not establish that a product is nontoxic, circular, economically preferable, or environmentally superior across its life cycle.

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Production and Manufacturing Case Study: Continuous Bioprocessing Innovation

Purpose and Objective

This case study examines how green and sustainable chemistry (GSC) considerations may be incorporated into pharmaceutical production and manufacturing through process intensification. It describes Merck & Co., Inc.'s transition from conventional batch manufacturing to integrated continuous bioprocessing for pembrolizumab and considers production capacity, equipment footprint, energy and water use, raw-material and consumable use, waste generation, process monitoring, and product quality. The therapeutic product remains unchanged while the manufacturing pathway and equipment configuration differ.

Overview

In 2024, Merck & Co., Inc. received the U.S. Environmental Protection Agency (USEPA) Green Chemistry Challenge Greener Synthetic Pathways Award for developing a continuous process to manufacture pembrolizumab, marketed as KEYTRUDA®. Pembrolizumab is a therapeutic protein that has traditionally been produced in large batches. In the continuous process, the protein is separated from the producing cells continuously rather than through a single filtration step at the end of a batch. According to the award profile, the process produces more pembrolizumab per unit of reactor volume, allowing use of smaller equipment and a smaller facility footprint while reducing specified energy, water, raw-material, and consumable requirements (USEPA OCSPP 2024).

Continuous manufacturing and other process-intensification approaches may use smaller equipment, integrated processing, automation, and real-time monitoring to improve process control and resource efficiency. Reported outcomes depend on the process, equipment, product, scale, and comparison used, and implementation may involve engineering, validation, economic, and regulatory considerations (Cravotto 2025). The quantitative results attributed to the pembrolizumab process in this case study are based on the USEPA award profile and Merck & Co., Inc.'s estimates.

Problem

Batch manufacturing of biologics may require large vessels and separate cultivation, filtration, purification, cleaning, and restart steps. The associated water, energy, consumable, raw-material, and waste requirements depend on the product, equipment, facility, and manufacturing process.

Process Design Approach

Merck & Co., Inc. developed an integrated continuous bioprocessing platform for pembrolizumab. The process uses continuous perfusion to maintain the cell culture while the therapeutic protein is continuously removed from the producing cells and processed, rather than relying on a single filtration step at the end of a large batch. According to USEPA, the higher production per unit of reactor volume allows the use of smaller equipment and more efficient use of filters and other consumables (USEPA OCSPP 2024).

Life-Cycle Pathway: Production and Manufacturing

- **Input:** Inputs include engineered cell cultures, growth media, water, energy, cleaning chemicals, filtration materials, single-use components, and other resources used to produce pembrolizumab.

- **Process:** During production and manufacturing, the integrated continuous platform uses perfusion to maintain the cell culture while the therapeutic protein is continuously separated from the cells and processed. Compared with the conventional batch process used as the baseline, the continuous process uses smaller equipment and integrates production and recovery steps. Process monitoring supports control of manufacturing conditions and product quality.
- **Output:** The process produces pembrolizumab through a different manufacturing configuration. USEPA reports increased production per unit of reactor volume and Merck & Co., Inc. estimates reductions in energy, water, and raw-material use compared with the company's batch-process baseline. Continuous process monitoring may also support product-quality control and reduce the potential for discarded off-specification material, although the sources reviewed do not quantify that waste reduction.

Outcomes and Potential Impacts

- **Resource and Waste Considerations:** The continuous process uses smaller equipment and uses consumables such as filters more efficiently. Merck & Co., Inc. estimates reduced raw-material use compared with its batch-process baseline. The reviewed award profile does not provide a complete waste inventory or identify all waste categories affected (USEPA OCSPP 2024).
- **Production per Reactor Volume:** According to USEPA, the process produces substantially more pembrolizumab per unit of reactor volume, allowing the use of smaller equipment and a smaller facility footprint (USEPA OCSPP 2024).
- **Worker-Exposure Considerations:** Closed and automated process steps may change opportunities for worker contact with process materials. The sources reviewed do not provide sufficient occupational-exposure data to quantify or compare worker exposures for the continuous and batch processes.
- **Estimated Resource Use:** Merck & Co., Inc. estimates that the continuous single-use process reduces energy consumption for pembrolizumab production by approximately 4.5-fold, water use by approximately 4-fold, and raw-material use by approximately 2-fold compared with the company's batch-process baseline (USEPA OCSPP 2024). These are company estimates reported in the USEPA award profile; the profile does not provide the complete underlying inventory, system boundary, or calculation method.

Relevant Green and Sustainable Chemistry Considerations

- **Waste Prevention:** Continuous protein recovery and more efficient use of consumables may reduce selected material and waste requirements relative to the batch-process baseline. The sources reviewed do not provide a complete comparison of all waste streams.
- **Energy and Facility Considerations:** Smaller equipment and a smaller facility footprint are associated with lower reported energy use. Merck & Co., Inc. estimates reduced energy consumption, but a complete comparative carbon-footprint or life-cycle assessment was not included in the sources reviewed.
- **Process Monitoring and Quality Control:** Integrated monitoring can provide information about process conditions and product quality. The sources reviewed do not quantify the amount of off-specification material avoided by this system.
- **Process-Safety Considerations:** Smaller, closed, or automated equipment may alter process-safety and occupational-exposure conditions. A comparison of accident scenarios, containment, cleaning chemicals, biological materials, and worker tasks would be needed to determine whether the continuous process presents a more favorable safety profile.

Relevance to Sustainable Systems

This case study examines how a change in manufacturing configuration can affect production capacity, equipment footprint, resource use, consumables, waste, process monitoring, and product-quality controls without changing the intended therapeutic product. The USEPA award profile reports company-estimated reductions in energy, water, and raw-material use relative to Merck & Co., Inc.'s batch-process baseline. The example illustrates that GSC considerations can apply to the design of manufacturing processes and equipment as well as to the chemical or biological product itself. Conclusions are specific to the pembrolizumab process, comparison baseline, facility configuration, and company estimates reported in the available sources and should not be generalized to all continuous or batch bioprocesses.

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Distribution and Packaging Case Study: Mycelium-Based Alternative to Expanded Polystyrene Packaging

Purpose and Objective

This case study examines how green and sustainable chemistry (GSC) considerations may be incorporated into protective-packaging design and manufacturing. It describes a mycelium-based composite made from minimally processed industrial-hemp stalks and considers feedstock requirements, biological manufacturing, compressive performance, energy and resource use, scalability, and potential end-of-life pathways. The example also identifies comparisons and data gaps relevant to evaluating the material as an alternative to expanded polystyrene (EPS) packaging.

Overview

EPS is used in food-service and protective packaging because it is lightweight, relatively inexpensive, and provides cushioning and insulation. EPS is produced from petrochemical feedstocks and is not biodegradable or compostable. Its low density and contamination or collection challenges can also limit recycling in some locations. These characteristics have contributed to interest in alternatives made from biobased or biodegradable materials. Mycelium-based composites are one potential option (Bhaskar et al. 2026). Mycelium-based composites use fungal mycelium as a biological binder within a lignocellulosic substrate. The study evaluated minimally processed hemp stalks without separating the bast-and-hurd fractions, a processing step that can require specialized equipment and lead to additional costs. Different hemp-feedstock ratios were combined with three fungal strains, and the resulting composites were tested for compressive strength relative to EPS (Bhaskar et al. 2026).

The case study is relevant to GSC because it considers an alternative feedstock, a biological binding process, reduced feedstock preprocessing, functional performance, and a potential biological end-of-life pathway. These attributes do not by themselves establish that the composite is preferable to EPS across all life-cycle categories. A broader comparison would need to consider fungal strain and substrate composition, cultivation and drying requirements, additives or coatings, product density and protective performance, transportation, use conditions, moisture sensitivity, and actual disposal or composting pathways.

Problem

EPS is a petrochemical-derived foam that is lightweight and effective in cushioning and insulation applications but is not biodegradable or compostable. Recycling may be limited by collection, contamination, transportation, and economic constraints. As a result, discarded EPS may persist in landfills or enter the environment.

Material Design Approach

The study evaluated mycelium-based composites as potential protective-packaging materials. Fungal mycelium grows through chopped hemp biomass and acts as a biological binder, producing a lightweight composite after growth and drying. Some tested combinations of hemp-feedstock ratio and fungal strain had compressive strengths that met or exceeded the EPS samples used as comparators (Bhaskar et al. 2026). The study focused primarily on compressive strength; broader protective performance may also depend on impact absorption, resilience after repeated loading, density, geometry, humidity, water exposure, temperature, and storage conditions.

The growth and drying process also raises application-specific health and safety questions. Relevant considerations may include whether the completed material contains viable fungal material, can release spores or particles, or presents allergen or microbial-growth concerns during manufacture, storage, use, or disposal. The primary study focused on material preparation and compressive performance and did not provide a complete occupational- or consumer-exposure assessment.

Use of minimally processed or locally available feedstocks may reduce some preprocessing or transportation requirements, but the primary study did not quantify transportation distances, associated emissions, or a complete supply-chain comparison.

Life-Cycle Pathway: Distribution

- **Input:** The primary inputs evaluated were minimally processed industrial-hemp stalks and mycelium from three selected fungal strains. The hemp substrate provides the plant-based structure, while fungal growth binds the substrate into a composite.
- **Process:** Chopped hemp substrate is prepared, inoculated with fungal material, and maintained under controlled conditions while the mycelium grows through and binds the substrate. The formed composite is subsequently dried to stop growth and stabilize the material. The study avoided separation of the hemp's bast-and-hurd fractions, reducing one feedstock-processing step. Energy, water, sterilization, drying, contamination control, production time, and scale remain relevant manufacturing considerations.
- **Output:** The study produced mycelium-hemp composite samples and compared their compressive strength with EPS samples. Some formulations met or exceeded the comparator's compressive strength under the test conditions. Additional testing would be needed to evaluate cushioning, repeated impacts, vibration, moisture exposure, dimensional stability, thermal insulation, storage life, product protection, and performance across different packaging geometries.

Outcomes and Potential Impacts

- **Feedstock Considerations:** Replacing an EPS component with a mycelium-hemp composite could reduce direct use of fossil-derived EPS in that packaging application. A broader resource comparison would also consider hemp production, substrate preparation, fungal cultivation, drying, transportation, and any coatings or other formulation components.
- **Potential End-of-Life Pathways:** Uncoated mycelium-lignocellulosic composites may be biodegradable under suitable biological conditions. Actual degradation or composting depends on the complete formulation, product density, temperature, moisture, microbial activity, coatings, collection, facility acceptance, and disposal environment. Biodegradability does not establish that the product will reach or perform appropriately in a composting system.
- **Feedstock Processing:** Use of minimally processed hemp stalks avoids the bast-and-hurd separation step evaluated by the researchers. Potential resource or cost implications depend on existing uses of the hemp material, preparation requirements, yields, cultivation time, contamination losses, drying, and manufacturing scale.
- **Distribution Considerations:** Packaging density, dimensions, protective performance, moisture sensitivity, storage conditions, shipping distance, and product-loss rates can influence distribution impacts. The primary study did not provide a comparative transportation analysis or full life-cycle assessment.
- **Implementation Considerations:** Broader adoption would require evaluation of protective performance across applications, moisture sensitivity, consistency among biological production batches, contamination control, manufacturing time, scalability, cost, feedstock availability, transport

and storage requirements, coatings or additives, facility acceptance, and realistic composting, degradation, or disposal pathways.

Relevant Green and Sustainable Chemistry Considerations

- **Potential Material Substitution:** Use of a mycelium-hemp composite could replace EPS in selected protective-packaging components, depending on performance and application requirements.
- **Hazard and Exposure Considerations:** Biological and plant-based feedstocks have different hazard and exposure characteristics from EPS. Relevant questions include dust, spores, allergens, microbial contamination, additives or coatings, worker exposure during cultivation and processing, and degradation products.
- **Energy and Process Requirements:** Avoiding fiber separation may reduce one preprocessing requirement. Biological growth occurs under comparatively mild temperature conditions, but drying, sterilization or pasteurization, environmental control, contamination management, and processing time may require energy and other resources. A comparative energy assessment was not reported.
- **Renewable and Secondary Feedstocks:** Industrial hemp is a renewable feedstock, and minimally processed stalk material may provide a lower processing input than separated hemp fibers. Resource implications depend on cultivation, land and water use, existing markets, transportation, and processing requirements.
- **Manufacturing and Supply-Chain Considerations:** Minimally processed hemp may simplify feedstock preparation, while biological manufacturing introduces requirements involving growth time, quality control, contamination prevention, drying, storage, and consistent supply.
- **Biological End-of-Life Considerations:** Uncoated mycelium-hemp composites may be compatible with biological degradation or composting under appropriate conditions. Product-specific testing and facility acceptance are needed to establish compostability, degradation time, residual quality, and compatibility with actual collection and treatment systems.

Relevance to Sustainable Systems

This case study examines a mycelium-based composite made with minimally processed industrial hemp as a potential alternative to EPS in selected protective-packaging applications. The study compared compressive strength among different fungal strains and hemp-feedstock ratios and reported that some formulations met or exceeded the EPS comparator under the tested conditions. The example illustrates how feedstock selection, biological manufacturing, preprocessing, protective performance, transportation, moisture sensitivity, scalability, and end-of-life conditions may affect evaluation of a packaging alternative. A complete comparison would require additional information about manufacturing inputs, energy and emissions, occupational and consumer exposures, coatings or additives, transport, product protection, cost, and realistic degradation, composting, or disposal pathways. The findings do not establish that every mycelium-based product is safer or environmentally preferable to every EPS packaging application.

Reference

Bhaskar, Radika, Tanisha Rutledge, Kevin Trangone, and Oneal Latimore. 2026. “Mycelium-Based Composites Using Minimally Processed Industrial Hemp Biomass: Impact of Species and Feedstock Ratio on Mechanical Performance Compared to Polystyrene Packaging.” *Polymers* 18 (3): 400. https://doi.org/10.3390/polym18030400.

End-of-Life Management Case Study: Nickel Catalyst for Polyolefin Recycling

Purpose and Objective

This case study examines the application of green and sustainable chemistry considerations to the catalytic treatment of selected polyolefin waste streams. It describes a regenerable, single-site nickel catalyst evaluated for hydrogenolysis of polyethylene and isotactic-polypropylene mixtures and isotactic polypropylene containing polyvinyl chloride (PVC). The case study also identifies considerations and data gaps involving feed composition and pretreatment, catalyst performance and regeneration, reaction conditions, hydrogen and energy requirements, product yields and quality, residuals, scale-up, life-cycle impacts, and comparison with other management pathways.

Overview

Researchers at Northwestern University and collaborating institutions developed a supported, single-site organonickel catalyst that selectively cleaves carbon-carbon bonds in selected polyolefins through hydrogenolysis (Lai et al. 2025). The researchers evaluated prepared mixtures of polyethylene and isotactic polypropylene, as well as isotactic polypropylene admixed with PVC. The catalyst preferentially cleaved branched carbon-carbon linkages, enabling the hydrogenolytic separation of polyethylene and isotactic polypropylene in the mixtures evaluated. It also remained active and selective during hydrogenolysis of isotactic polypropylene containing PVC under the tested conditions. The reported products included shorter-chain hydrocarbon oils and waxes that may be suitable for further processing or use in selected fuel, lubricant, wax, or chemical applications, depending on their composition, purity, and applicable product specifications. The spent catalyst was regenerated using triethylaluminum and reused in repeated experimental cycles (Lai et al. 2025). The underlying study describes these findings as demonstrating the potential of nickel-based systems for selective upcycling of complex plastic waste streams rather than establishing commercial-scale performance.

Polyethylene and polypropylene are used in products such as grocery bags, films, bottles, food packaging, disposable utensils, and other consumer and industrial applications. The study evaluated selected polymers and prepared mixtures rather than every product type represented by these examples or a general mixed postconsumer-plastic stream. The findings indicate potential for processing selected polyethylene and isotactic-polypropylene mixtures without complete separation of those two polymers and for processing isotactic polypropylene containing PVC under the conditions evaluated (Lai et al. 2025).

Problem

End-of-life management of polyolefin plastics can be affected by collection and sorting requirements, contamination, degradation of material properties, product design, and the technical and economic limitations of available recycling or conversion processes. Polyolefins that are not recovered may be landfilled, combusted, or released into the environment. Mixed-polymer streams and contaminants can create additional challenges because polymers and additives may respond differently to mechanical recycling, chemical conversion, treatment, or disposal.

Catalytic Conversion Approach

The study evaluated a supported, single-site organonickel catalyst for hydrogenolysis of selected polyethylene and isotactic-polypropylene mixtures and isotactic polypropylene containing PVC. In the presence of hydrogen, the active nickel-hydride catalyst preferentially cleaves selected carbon-carbon

linkages, producing shorter-chain hydrocarbon products. The spent catalyst was regenerated through treatment with triethylaluminum and reused in repeated experimental cycles (Lai et al. 2025). The primary study supports the catalyst's selective activity in the tested polymer mixtures and its repeated regeneration under experimental conditions.

The catalyst remained active and selective in the isotactic-polypropylene/PVC mixtures evaluated, and the researchers reported enhanced hydrogenolysis behavior under certain tested conditions. These findings indicate potential tolerance of PVC in the specific mixtures and conditions evaluated. They do not establish compatibility with every PVC concentration, additive package, contaminant, mixed-plastic stream, or postconsumer feedstock.

Evaluation at a larger scale would require additional information about feed composition and pretreatment; reaction temperature, hydrogen pressure, and reaction time; hydrogen demand and source; catalyst loading, lifetime, recovery, and regeneration; triethylaluminum and other regeneration inputs; product conversion, yields, composition, purity, and quality; chlorine-containing products and other process residuals; emissions and occupational or process-safety considerations; economics and throughput; and comparison with mechanical recycling, other chemical-conversion processes, energy recovery, and disposal.

Life-Cycle Pathway: End-of-Life Management

- **Input:** The research evaluated selected polyethylene and isotactic-polypropylene materials and mixtures, including isotactic polypropylene admixed with PVC. Potential future feedstocks could include postconsumer or postindustrial polyolefin waste, but performance with actual waste would depend on polymer composition, additives, moisture, dirt, food residue, labels, fillers, metals, other polymers, and required pretreatment.
- **Process:** The selected polymer feed is contacted with the supported nickel catalyst in the presence of hydrogen. The catalyst cleaves polymer carbon-carbon bonds to form shorter-chain hydrocarbon products. The complete case study should report the temperature, hydrogen pressure, reaction time, catalyst loading, polymer-to-catalyst ratio, pretreatment, conversion, and comparator conditions used in the underlying experiments. The laboratory experiments indicate that complete separation of polyethylene from isotactic polypropylene, or removal of PVC from the selected isotactic-polypropylene/PVC mixtures, was not required under the tested conditions. Other feed components or contaminants may still require separation or pretreatment.
- **Output:** The reported reaction products included shorter-chain hydrocarbon oils and waxes. Potential downstream uses may include fuels, lubricants, wax products, or chemical feedstocks, depending on composition, purity, additives, chlorine content, separation requirements, and product specifications. Conversion to fuels would recover energy or product value but would not return the carbon to a polymer material loop.
- **Catalyst Regeneration:** The researchers regenerated the spent catalyst using triethylaluminum treatment and evaluated reuse over repeated experimental cycles. This reuse reduces the need for fresh catalyst material. A broader assessment would consider activity and selectivity after regeneration, the number of effective cycles, regeneration yield, triethylaluminum and solvent requirements, handling hazards, nickel loss, support stability, residuals, and catalyst recovery at scale.

Outcomes and Potential Impacts

- **Selected Mixed and Contaminated Feedstocks:** The study demonstrated hydrogenolysis of selected polyethylene/isotactic-polypropylene mixtures and isotactic polypropylene admixed with PVC. Performance with broader postconsumer waste streams remains to be established.

- **Reaction Conditions:** The catalytic process operates under hydrogenolysis conditions that differ from thermal cracking or pyrolysis. Any energy comparison should include reaction temperature and pressure, hydrogen production and compression, pretreatment, catalyst preparation and regeneration, separation, product upgrading, throughput, and facility scale.
- **Product Recovery:** The process converts selected polyolefins into shorter-chain hydrocarbon products that may have value in fuel, lubricant, wax, or chemical applications. The degree of circularity depends on the final product and whether the recovered carbon returns to material production, is used in a shorter-lived product, or is ultimately combusted.
- **Potential Diversion:** If the process proves technically and economically feasible at scale and can accept relevant waste streams, it could provide an additional management pathway for selected polyolefin waste. Net diversion would depend on collection, sorting, preprocessing, facility capacity, product markets, and competition with other management options.
- **Implementation Considerations:** Further assessment is needed for feed variability and pretreatment, catalyst durability and regeneration, hydrogen sourcing and use, reaction energy, product yields and quality, chlorine-containing products and process residuals, emissions, occupational and process safety, economics, scale-up, and comparative life-cycle impacts.

Relevant Green and Sustainable Chemistry Considerations

- **Waste Management Pathway:** The process may provide an additional conversion pathway for selected polyolefin waste streams. Whether it prevents disposal or environmental release depends on collection, process performance, scale, economics, and product disposition**.**
- **Products and Residuals:** Product composition, chlorine-containing products, catalyst residues, additives, solvents, regeneration chemicals, emissions, and other process residuals should be characterized to evaluate potential hazards and downstream uses.
- **Energy and Hydrogen Requirements:** Catalytic hydrogenolysis may operate at lower temperatures than some thermal-conversion processes, but energy performance depends on temperature, pressure, hydrogen production and compression, reaction time, conversion, separations, regeneration, and scale. A complete comparison was not presented in the case study.
- **Catalyst-Metal Selection:** Nickel can provide an alternative to noble-metal hydrogenolysis catalysts. Evaluation should also consider nickel sourcing, catalyst loading, support materials, preparation, regeneration inputs, recovery, metal loss, toxicity, and end-of-life management.
- **Catalysis:** The single-site design provided selective activity for specified polyolefin linkages under the tested conditions. Catalyst activity, selectivity, lifetime, regeneration, and performance with realistic feedstocks remain relevant to scale-up.
- **Circularity Considerations:** Conversion of polyolefin waste into hydrocarbon products may retain some material or economic value. Whether the process supports circularity depends on feedstock displacement, product use, product lifetime, carbon retention, process inputs, residuals, and comparison with mechanical recycling, reuse, energy recovery, and disposal.

Relevance to Polyolefin End-of-Life Management

This case study examines a supported organonickel catalyst for hydrogenolysis of selected polyethylene and isotactic-polypropylene mixtures, including isotactic polypropylene admixed with PVC. The study also evaluated regeneration and reuse of spent catalyst. The example illustrates how catalyst selection, feed composition, contaminant tolerance, reaction conditions, hydrogen use, product quality, residual management, and catalyst regeneration may affect evaluation of a chemical-conversion pathway. Additional evidence would be needed to establish performance with realistic postconsumer feedstocks, commercial scale, environmental and occupational implications, economics, and comparative

performance against reuse, mechanical recycling, other chemical-conversion processes, energy recovery, and disposal. The reported findings do not establish that this process is appropriate for every polyolefin waste stream or that every resulting product closes a material loop.

Reference

Lai, Qingheng, Xinrui Zhang, Shan Jiang, et al. 2025. "Stable Single-Site Organonickel Catalyst Preferentially Hydrogenolyses Branched Polyolefin C–C Bonds." *Nature Chemistry* 17 (10): 1488–96. **https://doi.org/10.1038/s41557-025-01892-y**.

Case Study: Sustainable Aviation Fuel

Purpose and Objective

This case study examines how green and sustainable chemistry considerations may apply across the life cycle of sustainable aviation fuel (SAF). It describes selected feedstocks and conversion pathways, fuel-performance and certification requirements, compatibility with existing aviation systems, and factors affecting life-cycle greenhouse-gas emissions. It also considers particulate emissions, non-CO_2 climate effects, feedstock availability, process energy and hydrogen requirements, infrastructure, cost, and other implementation considerations. Environmental and emissions outcomes vary by feedstock, conversion pathway, energy source, system boundary, accounting method, and fuel blend.

Overview

Aviation contributes approximately 2 percent to 2.5 percent of global carbon dioxide emissions. Its total contribution to climate forcing is greater when non-CO_2 effects, including nitrogen oxides, contrail cirrus, water vapor, and particulate emissions, are considered. The magnitude and direction of these effects vary with fuel composition, aircraft and engine characteristics, flight conditions, altitude, weather, and atmospheric conditions (Lee et al. 2021; Ritchie 2024).

Problem

Aviation presents particular decarbonization challenges because aircraft require fuels or energy-storage systems with high energy density. Current battery technology is generally less suitable for long-distance large-aircraft applications because of battery mass and associated payload and range constraints, although electrification may have potential in selected shorter-range applications (Pattanayak and Mavris 2025). SAF is therefore one pathway being evaluated for reducing life-cycle greenhouse-gas emissions while retaining compatibility with existing aircraft and fuel infrastructure.

Reported life-cycle greenhouse-gas reductions vary substantially by feedstock, conversion process, energy and hydrogen sources, coproduct treatment, land-use assumptions, transportation, system boundary, and accounting method. The U.S. SAF Grand Challenge uses a goal of at least a 50 percent reduction in life-cycle emissions compared with conventional jet fuel; individual pathway results may be higher or lower depending on the applicable methodology and circumstances (USDOE 2022, 2026).

Sustainable Aviation Fuel Production and Use Approach

SAF includes aviation fuels produced from nonpetroleum or alternative carbon feedstocks through approved conversion pathways. Depending on the pathway, feedstocks may include fats, oils, greases, agricultural or forestry materials, municipal or industrial waste streams, alcohols, or carbon-containing gases. Production may require hydrogen, catalysts, electricity, heat, water, solvents, and other process inputs.

Some SAF blending components have lower aromatic content than conventional petroleum jet fuel. Lower-aromatic fuel blends can reduce soot and particulate emissions under certain combustion conditions and may influence contrail formation and non-CO_2 climate effects. The magnitude of these effects depends on fuel composition, blending level, engine, operating conditions, route, weather, and atmospheric conditions (Zheng et al. 2021).

SAF blending components must satisfy applicable fuel specifications and pathway-specific blending limits before use in existing aircraft and fueling systems. Current approved pathways have different feedstock, production, composition, and blending requirements. Certified SAF is generally blended with

conventional jet fuel before distribution or use; broad commercial use of unblended SAF is not currently permitted under existing ASTM International fuel specifications (USDOE 2026).

Several conversion pathways have been approved for producing SAF blending components from different feedstocks. These pathways use different chemical and biological processes and have pathway-specific fuel-composition and blending requirements. When certified, blended within the applicable limit, and shown to meet the relevant fuel specification, the finished fuel can be used in existing aircraft and fueling infrastructure (USDOE 2026). Prominent pathways include the following:

- **Hydroprocessed Esters and Fatty Acids (HEFA):** HEFA converts lipid feedstocks, such as used cooking oil, animal fats, or vegetable oils, through processes that may include pretreatment, deoxygenation, hydroprocessing, and hydrocracking. HEFA is among the more commercially mature SAF pathways. Life-cycle emissions depend on feedstock origin, existing or counterfactual feedstock uses, collection and transportation, hydrogen and energy sources, processing, coproduct treatment, and land-use effects. Lipid-feedstock availability, competing uses, cost, and sustainability criteria may limit expansion (Khujamberdiev and Cho 2024).
- **Alcohol-to-Jet (ATJ):** ATJ pathways convert alcohols such as ethanol or isobutanol into aviation-range hydrocarbons through dehydration, oligomerization, hydrogenation, and related processing steps. Alcohols may be produced from several feedstocks rather than only waste streams. Life-cycle performance depends on alcohol production, feedstock sourcing, process energy, hydrogen use, conversion efficiency, coproducts, and transportation. Current considerations include production cost, process integration, and commercial scale (Khujamberdiev and Cho 2024).
- **Fischer-Tropsch (FT) Synthesis:** FT pathways convert synthesis gas, composed primarily of carbon monoxide and hydrogen, into liquid hydrocarbons. Synthesis gas can be derived from several sources, including biomass, wastes, natural gas, or coal, but use of a particular feedstock does not necessarily qualify the resulting fuel as SAF or produce the same life-cycle emissions. Relevant considerations include gasification or reforming, feedstock supply, hydrogen and energy inputs, capital requirements, process scale, product upgrading, carbon conversion, and emissions (Khujamberdiev and Cho 2024).

Cross-Life-Cycle Pathway

- **Input:** Potential inputs include renewable, waste-derived, recycled-carbon, or other eligible feedstocks, together with hydrogen, catalysts, water, electricity, heat, and other process materials. Feedstock selection can affect land use, water use, competing uses, supply availability, transportation, conversion efficiency, cost, and life-cycle greenhouse-gas results.
- **Production and Manufacturing:** Feedstocks are converted into aviation-range hydrocarbons through approved pathways such as HEFA, ATJ, or FT synthesis. Production requirements vary and may include pretreatment, hydrogen production and use, catalytic conversion, separation, upgrading, blending, and quality control. Fuel composition must meet applicable specifications for properties such as energy density, freezing point, thermal stability, combustion performance, material compatibility, and approved aromatic content.
- **Distribution and Infrastructure**: Approved SAF blending components are generally transported to blending facilities, blended with conventional jet fuel within pathway-specific limits, certified as meeting the applicable fuel specification, and distributed through existing fuel infrastructure. Infrastructure compatibility may reduce the need for changes to aircraft or airport fuel systems, but blending, quality assurance, transportation, storage, accounting, and feedstock logistics remain relevant.
- **Use**: SAF blends are combusted in aircraft in the same general manner as conventional jet fuel. Potential changes in particulate emissions and contrail-related effects depend on final fuel

composition, blending level, aircraft and engine characteristics, route, weather, and atmospheric conditions.

- **Output and End of Life:** The principal output is a certified SAF blending component or finished fuel blend for aviation use. Combustion releases carbon dioxide and other emissions; SAF does not eliminate tailpipe carbon emissions. Potential climate benefits are evaluated on a life-cycle basis by accounting for feedstock production or collection, conversion, transportation, blending, combustion, coproducts, and other factors within the chosen system boundary.

Outcomes and Potential Impacts

- **Life-Cycle Greenhouse-Gas Emissions:** Some SAF pathways may reduce life-cycle greenhouse-gas emissions relative to conventional petroleum jet fuel. Results vary by feedstock, pathway, energy and hydrogen sources, land-use assumptions, coproduct accounting, transportation, conversion efficiency, blending level, and assessment method. The U.S. SAF Grand Challenge uses a target of at least a 50 percent reduction; this target does not establish the performance of every pathway or facility.
- **Particulate and Non-CO_2 Effects:** Lower-aromatic SAF blends can reduce soot and particulate emissions under selected conditions and may affect contrail formation. Actual non-$C0_2$ climate effects depend on fuel composition, blend level, engine, route, altitude, weather, and atmospheric conditions (Lee et al. 2021; Zheng et al. 2021).
- **Feedstock and Resource Considerations:** SAF pathways can use several renewable, waste-derived, or alternative carbon feedstocks. Potential benefits and tradeoffs depend on availability, quality, competing uses, land and water requirements, collection and transportation, processing, and whether the feedstock would otherwise be used, stored, treated, or disposed of.
- **Infrastructure Compatibility:** Certified SAF blends can be used within existing aircraft and fuel infrastructure under applicable specifications and approved blending limits. Logistics, blending equipment, quality assurance, storage, transportation, and regional fuel availability may still affect implementation.
- **Implementation Considerations:** Implementation depends on eligible feedstock supply, production capacity, energy and hydrogen sources, cost, certification, blending, logistics, infrastructure, policy and market conditions, and verified life-cycle performance. Limited available production and consumption data may also affect evaluation of market-scale outcomes.

Relevant Green and Sustainable Chemistry Considerations

- **Feedstock Selection:** Some SAF pathways use renewable, waste-derived, or recycled-carbon feedstocks rather than newly extracted petroleum. Renewable or waste-derived origin does not by itself establish favorable life-cycle performance; sourcing, competing uses, processing, transportation, and land-use implications remain relevant.
- **Energy and Process Requirements:** SAF production may require substantial heat, electricity, hydrogen, pressure, separation, and upgrading. Energy requirements vary among pathways and can materially affect life-cycle greenhouse-gas results. Process efficiency should therefore be evaluated for the specific pathway and facility.
- **Fuel Composition and Combustion Emissions:** Lower-aromatic SAF blending components may reduce soot and particulate formation under selected combustion conditions. Evaluation should consider final blend composition, engine performance, material compatibility, regulated emissions, and non-CO_2 climate effects.
- **Life-Cycle Thinking**: Comparison with conventional jet fuel may include feedstock production or collection, land and water use, conversion, process energy and hydrogen, transportation, blending,

infrastructure, combustion, coproducts, and indirect effects. Results depend on the assessment method, system boundary, data, and assumptions.

Relevance to Sustainable Systems

This case study examines SAF as a cross-life-cycle application involving feedstock sourcing, chemical conversion, fuel certification, transportation and blending, existing aviation infrastructure, combustion, and life-cycle greenhouse-gas accounting. SAF may provide lower life-cycle greenhouse-gas emissions than conventional petroleum jet fuel for some pathways and conditions while maintaining compatibility with existing aviation systems within approved specifications and blending limits. The magnitude and distribution of potential benefits and tradeoffs depend on feedstock selection, land and water use, process energy and hydrogen, conversion efficiency, infrastructure, emissions, coproducts, cost, scale, and the life-cycle methodology applied. The example does not establish that every SAF pathway is renewable, circular, carbon negative, or environmentally preferable across all relevant attributes.

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Zheng, Lukai, Paramvir Singh, James Cronly, et al. 2021. "Impact of Aromatic Structures and Content in Formulated Fuel for Jet Engine Applications on Particulate Matter Emissions." *Journal of Energy Resources Technology* 143 (122301). **https://doi.org/10.1115/1.4049905**.

Case Study: Regenerable Treatment Material for Selected PFAS

Purpose and Objective

This case study describes a laboratory-scale copper-aluminum layered double hydroxide (LDH) platform evaluated for adsorption of selected anionic per- and polyfluoroalkyl substances (PFAS) and for thermal regeneration after adsorption of perfluorooctanoic acid (PFOA). Thermal treatment produced partial PFOA defluorination rather than complete destruction of all adsorbed PFAS. The case study summarizes the demonstrated results and identifies evidence gaps that remain before field-scale application.

Overview

Researchers at Rice University, in collaboration with international partners, developed a laboratory-scale copper-aluminum LDH material for rapid adsorption of the selected anionic PFAS—specifically, PFOA, perfluorooctane sulfonic acid (PFOS), perfluorononanoic acid (PFNA), and perfluorohexane sulfonic acid (PFHxS)—from water. The study also demonstrated partial defluorination of PFOA during thermal treatment with calcium carbonate rather than complete destruction of all PFAS. Thermal treatment of PFOA-loaded LDH with calcium carbonate regenerated the material and achieved approximately 54 percent defluorination of adsorbed PFOA under unoptimized laboratory conditions (Kim et al. 2025). The work is a proof of concept for an integrated capture–thermal treatment–reuse process; it does not demonstrate performance for all PFAS classes or at field scale. PFAS are highly persistent contaminants that have been detected in drinking water and other aquatic environments, and conventional treatment methods can suffer from low adsorption capacity, slow kinetics, and secondary waste challenges. This material offers a potential pathway for capture, partial PFOA defluorination, and sorbent reuse under laboratory conditions, although important scale-up, residual-management, and end-of-life questions remain.

Problem

Conventional PFAS treatment technologies, including activated carbon and ion-exchange resins, can generate PFAS-containing spent media or other secondary wastes. Adsorption capacity and kinetics vary with the treatment material, PFAS identity, water chemistry, operating conditions, and comparison used. These considerations have contributed to research on regenerable sorbents that combine contaminant capture with treatment or management of the adsorbed PFAS.

Treatment-Material Approach

A regenerable copper-aluminum LDH adsorbed the selected anionic PFAS, PFOA, PFOS, PFNA, and PFHxS, under the reported laboratory conditions. The positively charged layered structure enabled adsorption primarily through electrostatic attraction and anion exchange. For PFOA, the authors reported a maximum adsorption capacity of 1,702 mg/g and an adsorption rate constant of 13.2 h^{-1} at neutral pH and room temperature. Once loaded with PFOA, the material was thermally treated at 500°C with calcium carbonate under argon, achieving approximately 54 percent defluorination under unoptimized proof-of-concept conditions. The study therefore supports an integrated capture, regeneration, and reuse concept with partial PFOA defluorination, not complete destruction of PFOA or all PFAS (Kim et al. 2025).

Treatment and Material-Regeneration Pathway

- **Input:** Water containing the selected anionic PFAS (PFOA, PFOS, PFNA, and PFHxS) was evaluated in the study. Testing with environmental water matrices used PFOA-spiked drinking-water-treatment-plant influent, drinking-water-treatment-plant effluent, and wastewater-treatment-plant tertiary effluent.

- **Process:** Water was contacted with the LDH material in batch or continuous-flow systems. The selected anionic PFAS adsorb to positively charged LDH surfaces and interlayers through electrostatic attraction and anion exchange. For regeneration, PFOA-loaded material is thermally treated at 500°C with calcium carbonate under argon to convert the LDH to a layered double oxide and promote partial PFOA defluorination. During subsequent contact with water, the material can reconstruct into a PFOA-intercalated LDH phase upon exposure to PFOA anions, consistent with LDH memory effect.
- **Output:** Treated water had reduced concentrations of the selected anionic PFAS under the reported laboratory conditions. Performance varied with PFAS identity and water chemistry; competing organic and inorganic constituents reduced PFOA adsorption in some water matrices. Thermal treatment achieved approximately 54 percent defluorination of adsorbed PFOA. Residual PFOA or other fluorinated material, transformation products, required polishing steps, emissions, and final residual management remain unresolved.

Material Loop

The study demonstrated five PFOA adsorption and thermal-regeneration cycles. The initial adsorption rate declined from 10.0 h^{-1} during the first cycle to 4.0 h^{-1} during the fifth cycle. These results demonstrate repeated use under the laboratory conditions evaluated but do not establish maintained performance over longer operation or eliminate the need to manage spent material, residual PFAS, transformation products, and residual fluorine at the end of the treatment material's useful life.

Outcome and Potential Impacts

- **Selected PFAS Adsorption Performance:** The LDH demonstrated rapid adsorption of the tested anionic PFAS under laboratory conditions. For PFOA, the reported maximum batch adsorption capacity was 1,702 mg/g, and the adsorption rate constant was 13.2 h^{-1} at neutral pH and room temperature.
- **Continuous-Flow Demonstration:** PFOA removal was demonstrated in a small fixed-bed system using 0.5 g LDH mixed with 50 g sea sand in an approximately 15 mL bed, with 75 mg/L PFOA and flow rates of 0.5–2 mL/min. Additional testing would be needed to evaluate long-term performance under field-scale operating conditions.
- **Applicability Across PFAS:** Adsorption was demonstrated for PFOA, PFOS, PFNA, and PFHxS, but affinity varied by chain length and functional group. The results should not be generalized to all PFAS classes or mixed contaminant conditions without additional testing.
- **Regeneration and Waste Reduction Potential:** Thermal treatment with calcium carbonate regenerated the material and achieved approximately 54 percent PFOA defluorination under unoptimized proof-of-concept conditions. This suggests potential to reduce the frequency of sorbent replacement and the quantity of spent treatment material requiring management. It does not establish a reduction in total PFAS-containing residuals, complete PFOA destruction, or elimination of residual-waste-management requirements.
- **Implementation Considerations:** Broader application would require evaluation of complete fluorine and carbon mass balances; residual PFAS and transformation products; potential air emissions; calcium-containing and other residuals; regeneration durability; copper or aluminum leaching; energy, argon, and reagent requirements; performance in complex water matrices and at environmentally relevant concentrations; hydraulic performance and treatment capacity; final material disposition; process safety; cost; and scalability for municipal or industrial treatment systems.

Relevant Green and Sustainable Chemistry Considerations

- **Contaminant Transformation:** The study evaluated partial PFOA defluorination during thermal regeneration rather than indefinite containment of adsorbed PFOA. The approximately 54 percent defluorination result does not establish complete mineralization or characterize all transformation products and residual fluorine.
- **Treatment-Material Composition:** The sorbent uses copper and aluminum rather than rare or precious metals. Evaluation should also consider metal sourcing, material preparation, potential leaching, regeneration losses, recovery, and final disposal.
- **Regeneration and Material Reuse:** The treatment material can be regenerated and reused over five laboratory adsorption and thermal-treatment cycles, although adsorption rates declined over successive cycles.
- **Circularity Considerations:** The platform is intended to integrate adsorption, thermal regeneration, partial PFOA defluorination, and repeated use of the treatment material. Whether the process provides a circular or waste-reducing outcome depends on regeneration durability, energy and reagent inputs, emissions, residual PFAS and fluorine, metal recovery, final material management, and scale.

Relevance to Treatment-Material Design and Regeneration

This case study examines how contaminant capture, thermal treatment, and regeneration can be integrated into the design and operation of a functional water-treatment material. Its principal contribution is a laboratory-scale concept for adsorption of selected anionic PFAS, partial defluorination of adsorbed PFOA, and repeated use of the copper-aluminum LDH material. The example concerns treatment-material use and regeneration; it is not an example of managing the original PFAS-containing product at the end of its useful life. Before the system can be characterized as closed loop, PFAS-destroying, or waste avoiding, additional evidence is needed regarding complete fluorine and carbon mass balances, transformation products, residual PFAS, emissions, energy and reagent requirements, regeneration durability, final material disposition, treatment capacity, cost, and field-scale performance.

Reference

Kim, Keon-Han, Youngkun Chung, Philip Kenyon, et al. 2025. “Regenerable Water Remediation Platform for Ultrafast Capture and Mineralization of Per- and Polyfluoroalkyl Substances.” *Advanced Materials* 38 (1): e09842. https://doi.org/10.1002/adma.202509842.

APPENDIX B. SELECTED STATE EXAMPLES

Washington State Department of Ecology: Safer Products Restrictions and Reporting Rule

Purpose and Objective

This case study examines Washington State's framework for identifying priority chemicals and consumer products and adopting restrictions or reporting requirements for specified chemical-product combinations. It describes the recurring process established under Chapter 70A.350 of the Revised Code of Washington (RCW) and implemented through the Safer Products for Washington (SPWA) program and Chapter 173-337 of the Washington Administrative Code (WAC). The case study also considers how hazard, exposure, alternatives, product use, and regulatory implementation may relate to green and sustainable chemistry (GSC) concepts discussed in the Focus Sheet.

Overview

The Washington State Department of Ecology (WA ECY), in consultation with the Washington State Department of Health, implements Chapter 70A.350 RCW, commonly referred to as the Toxic Pollution Law, through the SPWA Program. Enacted in 2019, the law establishes an ongoing process for identifying and regulating priority chemicals in consumer products through recurring five-year cycles. Each cycle includes four phases: prioritizing chemicals, identifying priority consumer products, determining regulatory actions, and rulemaking (Chapter 70A.350 RCW; WA ECY 2026).

In Phase 1, WA ECY identifies priority chemicals or chemical classes. In Phase 2, the agency identifies priority consumer products that are significant sources or uses of those chemicals. In Phase 3, WA ECY evaluates potential regulatory actions, including whether restrictions or reporting requirements are warranted for specified chemical-product combinations. For restrictions, the process considers whether safer alternatives are feasible and available under the applicable statutory criteria. In Phase 4, WA ECY conducts rulemaking, including publication of proposed requirements and opportunities for public comment, before adopting final rules (Chapter 70A.350 RCW; Chapter 173-337 WAC: Safer Products Restrictions and Reporting).

Problem

Certain chemicals used in consumer products may present human health or environmental concerns because of their hazards, potential exposures, persistence, bioaccumulation, or presence in products and waste streams. State agencies may have limited information about where such chemicals are used and whether feasible alternatives are available for applications.

State Regulatory Framework

The SPWA program uses a recurring process to identify priority chemicals and products, evaluate potential regulatory actions, and adopt restrictions or reporting requirements through rulemaking. Depending on the chemical-product combination and applicable statutory findings, regulatory action may include restricting a priority chemical or requiring manufacturers to report its use. When evaluating potential restrictions, WA ECY assesses whether alternatives are safer, feasible, and available under the statutory framework. Alternatives may include another chemical, material, product design, process, or elimination of the chemical's function in the product.

The law may address individual chemicals or chemical classes. Class-based evaluations can help identify structurally or functionally related chemicals that could raise similar concerns, but they do not establish that every chemical within a class has the same hazard, exposure, performance, or regulatory status.

Program in Practice

The SPWA program demonstrates how the state's safer products policy is implemented through a recurring four-phase regulatory cycle. Each cycle moves from identifying chemicals of concern to evaluating priority products and safer alternatives, selecting regulatory actions, and adopting enforceable requirements.

1. **Phase 1—Identify Priority Chemicals or Chemical Classes:** WA ECY, in consultation with the Department of Health, identifies chemicals or chemical classes for evaluation under the statutory criteria.
2. **Phase 2—Identify Priority Consumer Products:** The state evaluates consumer products that are significant sources or uses of the priority chemicals and selects chemical-product combinations for further review.
3. **Phase 3—Evaluate Alternatives and Determine Regulatory Actions:** WA ECY evaluates hazards, potential exposures, and other statutory factors. When considering a restriction, the agency evaluates whether alternatives are safer, feasible, and available. Potential regulatory actions include restrictions or reporting requirements.
4. **Phase 4—Adopt and Implement Rules:** WA ECY conducts rulemaking, provides opportunities for public comment, completes applicable legislative reporting or review requirements, and adopts and implements final rules.

Outcomes and Potential Impacts

- **Potential Exposure Reduction:** Restrictions may reduce the presence of specified priority chemicals in covered consumer products and associated potential exposures. Reporting requirements provide information about chemical use but do not themselves restrict the chemical.
- **Alternatives Considerations:** Evaluation of safer, feasible, and available alternatives may provide information about whether a proposed substitute could shift hazards or impacts. Class-based evaluation may also help identify related chemicals that warrant consideration.
- **Potential Downstream Implications:** Reducing the use of a priority chemical in specified products may affect its presence in waste, recycling, environmental releases, or potential exposures. The magnitude of any resulting waste-management, cleanup, or public-health benefit depends on the chemical, product, implementation, compliance, and other sources of exposure.
- **Product and Market Responses:** Restrictions, reporting requirements, and alternatives evaluations may influence product formulation, material selection, supplier decisions, and the availability of alternatives. The magnitude and direction of these effects depend on the affected products, compliance options, market conditions, and implementation schedule.

Relevant Green and Sustainable Chemistry Considerations

- **Pollution Prevention:** Restrictions on specified priority chemical-product combinations may reduce the use of those chemicals in covered products and associated releases or waste streams.
- **Alternatives Assessment:** When evaluating restrictions, the program considers whether alternatives are safer, feasible, and available under the statutory framework.

- **Chemical-Class Considerations:** Evaluation of chemical classes may help identify related substances that could raise similar concerns, while recognizing that hazards, exposures, functions, and data may vary within a class.
- **Information and Transparency:** Reporting requirements provide information about the intentional use of specified priority chemicals in covered consumer products.
- **Circularity Considerations:** Restrictions on specified chemicals may affect the chemical content of products entering reuse, recycling, treatment, or disposal systems. Whether this improves material recovery depends on product composition, implementation, collection, processing, and the alternative selected.

Relevance to Sustainable Systems

This case study illustrates a state framework that identifies priority chemicals and consumer products and applies restrictions or reporting requirements to specified chemical-product combinations. The program includes consideration of hazards, potential exposures, alternatives, product uses, and regulatory implementation, which overlap with several GSC concepts discussed in the Focus Sheet. The example does not establish that every regulated chemical has the same hazard profile, that every alternative is preferable across all attributes, or that restrictions and reporting requirements produce identical outcomes.

Reference

WA ECY. 2026. "Safer Products for Washington — Washington State Department of Ecology." https://ecology.wa.gov/waste-toxics/reducing-toxic-chemicals/washingtons-toxics-in-products-laws/safer-products.

Minnesota Pollution Control Agency: PFAS In Products And Amara's Law

Purpose and Objective

This case study examines Minnesota's statutory framework for intentionally added per- and polyfluoroalkyl substances (PFAS) in products, commonly discussed as Amara's Law. It describes category-specific product prohibitions, PFAS-in-products reporting requirements, the broader prohibition scheduled for 2032, and the rulemaking process for determining currently unavoidable uses. The example also considers how product restrictions, reporting, alternatives, pollution prevention, and implementation relate to green and sustainable chemistry concepts discussed in this Focus Sheet.

Overview

Minnesota Statutes section 116.943 establishes reporting requirements and phased prohibitions for products containing intentionally added PFAS. The law is commonly discussed as Amara's Law and is administered by the Minnesota Pollution Control Agency (MN PCA). "Intentionally added" PFAS are PFAS deliberately added during manufacturing when their continued presence in the final product or a product component is desired to perform a specific function (Minnesota Statutes Section 116.943).

The law took effect in stages. Restrictions for 11 specified categories of new products began January 1, 2025. Reporting requirements apply to covered products containing intentionally added PFAS. A broader prohibition is scheduled for January 1, 2032, except for uses determined by rule to be currently unavoidable (Minnesota Statutes Section 116.943; MN PCA 2026a).

Problem

PFAS have been used in products to provide functions such as water, oil, stain, heat, or chemical resistance. Their environmental persistence and the difficulty and cost of managing PFAS contamination have contributed to governmental actions addressing intentionally added PFAS in products. Product and supply-chain information may also be incomplete, making it difficult to identify where PFAS are used, the functions they provide, and whether alternatives are available for particular applications.

State Regulatory Framework

The Minnesota framework combines category-specific product prohibitions, product reporting, a phased broader prohibition, and rulemaking for currently unavoidable use determinations. These mechanisms serve different functions. Restrictions prohibit the sale, offer for sale, or distribution for sale of covered products containing intentionally added PFAS. Reporting provides information about covered product uses and PFAS content. The currently unavoidable use process will determine which uses may be excepted from the broader prohibition scheduled for 2032 (Minnesota Statutes Section 116.943; MN PCA 2026a, 2026b).

Program in Practice

Amara's Law includes three principal implementation milestones: category-specific product prohibitions, PFAS-in-products reporting, and a broader prohibition accompanied by a process for determining currently unavoidable uses.

Category-Specific Prohibitions Beginning January 1, 2025

Beginning January 1, 2025, Minnesota prohibits the sale, offer for sale, or distribution for sale of new products containing intentionally added PFAS in the following 11 categories:

- carpets or rugs;
- cleaning products;
- cookware;
- cosmetics;
- dental floss;
- fabric treatments;
- juvenile products;
- menstruation products;
- textile furnishings;
- ski wax; and
- upholstered furniture.

The prohibitions are subject to statutory definitions and specified exclusions or limitations. Currently unavoidable use determinations do not apply to products covered by these category-specific prohibitions. Manufacturers and other regulated entities should consult Minnesota Statutes section 116.943 and current guidance from the MN PCA to determine whether a particular product is covered (Minnesota Statutes Section 116.943; MN PCA 2026a).

PFAS-in-Products Reporting

Manufacturers of covered products sold, offered for sale, or distributed in Minnesota must report information about products or product components containing intentionally added PFAS. Required information includes the following:

- a description or applicable product code for the product or product component;
- the purpose or function for which PFAS are used;
- identification of each PFAS or applicable PFAS category;
- the amount or applicable concentration range of PFAS in the product or component;
- manufacturer identification and contact information; and
- other information required under the statute or implementing rules.

The initial reporting deadline was September 15, 2026. Manufacturers that received an approved extension have until December 14, 2026, to submit their initial reports. Subsequent reports are due annually on February 1 when required information has changed or as otherwise provided under the applicable reporting requirements.

The statute and adopted reporting rules include exclusions, exemptions, product-grouping options, waiver provisions, trade-secret procedures, fees, and other implementation requirements. Reporting provides information about where intentionally added PFAS are used and the functions they perform, but reporting does not itself prohibit the reported use (Minnesota Statutes Section 116.943; MN PCA 2026b).

Broader Prohibition and Currently Unavoidable Uses Beginning January 1, 2032

Beginning January 1, 2032, a product containing intentionally added PFAS may not be sold, offered for sale, or distributed for sale in Minnesota unless the MN PCA has determined by rule that the PFAS use qualifies as a currently unavoidable use or another applicable statutory exclusion applies.

Minnesota law defines a currently unavoidable use as a use of PFAS that the MN PCA commissioner has determined by rule to be:

- essential for health, safety, or the functioning of society; and
- a use for which alternatives are not reasonably available.

The MN PCA is conducting a separate rulemaking process to establish the criteria and procedures for currently unavoidable use determinations. As of October 2026, that rulemaking remains underway. The case study should not imply that currently unavoidable use determinations have already been granted or that final criteria have been adopted (Minnesota Statutes Section 116.943; MN PCA 2026c).

Implementation Considerations

The phased schedule separates category-specific prohibitions, product reporting, and the broader 2032 prohibition. These mechanisms serve different purposes and have different implementation dates. The 2025 provisions prohibit intentionally added PFAS in specified product categories, the reporting program provides information about PFAS use in covered products, and the 2032 provision establishes a broader prohibition subject to currently unavoidable use determinations and applicable exclusions.

Implementation considerations include manufacturer and supplier outreach, collection and review of reported information, maintenance of the reporting system, compliance and enforcement, communication about exclusions and exemptions, rulemaking for currently unavoidable use determinations, and coordination with other applicable state and federal requirements. The effects of the law will depend on implementation, compliance, product reformulation, available alternatives, supply-chain information, and currently unavoidable use determinations.

Relationship to Product Life-Cycle Considerations

The Minnesota framework may affect multiple product life-cycle stages. Category-specific prohibitions and the broader 2032 prohibition may influence chemical selection, product design, formulation, manufacturing, and supplier decisions for products sold in Minnesota. Reporting requirements provide information about where intentionally added PFAS are used, the functions they serve, and their reported concentrations or concentration ranges. Restrictions may also affect which products and chemicals enter use, reuse, recycling, wastewater, treatment, and disposal systems.

These potential effects depend on implementation, compliance, product composition, alternative selection, currently unavoidable use determinations, and other PFAS sources. The law itself is not a complete alternatives assessment or life-cycle assessment and does not establish that every replacement has a more favorable hazard, exposure, performance, cost, or life-cycle profile.

Outcomes and Potential Impacts

- **Restrictions on Intentionally Added PFAS:** The law prohibits intentionally added PFAS in specified product categories and establishes a broader prohibition beginning in 2032, subject to currently unavoidable use determinations and applicable statutory or regulatory exclusions.
- **Potential Pollution-Prevention and Exposure Implications:** Restrictions may reduce the presence of intentionally added PFAS in covered products and associated releases or potential exposures. The magnitude of these effects will depend on compliance, product uses, alternative formulations, and other PFAS sources.
- **Product and Market Responses:** Reporting, restrictions, and the broader 2032 prohibition may influence product formulation, material selection, supplier communication, product availability, and

evaluation of alternatives. The law does not by itself establish that every substitute is safer or environmentally preferable across all relevant attributes.

- **Potential Downstream Implications:** Reducing intentionally added PFAS in covered products may affect the quantity and types of PFAS entering wastewater, recycling, treatment, and disposal systems. The extent of any resulting reduction in contamination, treatment requirements, cleanup costs, or waste-management burdens depends on implementation, product lifetimes, existing products, other PFAS sources, and the alternatives selected.
- **Implementation Considerations:** Implementation includes reporting-system administration, manufacturer and supplier outreach, review of reported information, compliance and enforcement, currently unavoidable use rulemaking, communication about exclusions and exemptions, and coordination with other jurisdictions and regulatory programs.

Relevant Green and Sustainable Chemistry Considerations

- **Pollution Prevention:** Product restrictions may reduce the intentional use of PFAS in covered products before those chemicals enter use, waste, wastewater, recycling, treatment, or disposal systems.
- **Alternatives Considerations:** Restrictions and the broader prohibition may lead manufacturers to consider alternative chemicals, materials, product designs, processes, or functions. Evaluation of an alternative may include hazard, exposure potential, performance, technical feasibility, availability, cost, and life-cycle implications. The law does not establish that every replacement is inherently safer.
- **Information and Transparency:** Reporting requirements provide information about products containing intentionally added PFAS, the PFAS function, and the reported amount or concentration range. This information may support implementation, public information, and future regulatory evaluation.
- **Function and Feasibility:** The currently unavoidable use process is intended to identify uses that are essential for health, safety, or the functioning of society and for which alternatives are not reasonably available under the applicable rule.

Relevance to Sustainable Systems

This case study illustrates a state framework that combines product reporting, category-specific restrictions, a phased broader prohibition, and a process for determining currently unavoidable uses of intentionally added PFAS. These mechanisms may influence chemical selection, product formulation, supply-chain information, product availability, and which chemicals enter use and downstream waste-management systems. The example does not establish that every PFAS use presents the same hazard or exposure, that every alternative is preferable across all relevant attributes, or that reporting and restrictions produce identical outcomes.

References

MN PCA. 2026a. “2025 PFAS Prohibitions.” https://www.pca.state.mn.us/air-water-land-climate/2025-pfas-prohibitions.

MN PCA. 2026b. “PFAS in Products | Minnesota Pollution Control Agency.” https://www.pca.state.mn.us/get-engaged/pfas-in-products.

MN PCA. 2026c. “PFAS in Products: Currently Unavoidable Use | Minnesota Pollution Control Agency.” https://www.pca.state.mn.us/get-engaged/pfas-in-products-currently-unavoidable-use.

California Department of Toxic Substances Control: Safer Consumer Products Program

Purpose and Objective

This case study examines California's framework for identifying specified consumer product-chemical combinations that require alternatives analysis or other applicable compliance actions and selecting regulatory responses. It describes the Safer Consumer Products (SCP) Program's Candidate Chemicals List, Priority Product process, alternatives-analysis requirements, and regulatory authority. The case study also considers how hazard, exposure potential, product function, performance, alternatives, and regulatory implementation relate to green and sustainable chemistry (GSC) concepts discussed in this Focus Sheet.

Overview

The California Department of Toxic Substances Control (CA DTSC) implements the SCP Program under California's Green Chemistry laws and the SCP Regulations, which took effect in 2013. The regulatory framework provides a process for identifying consumer product-chemical combinations as Priority Products, requiring responsible entities to evaluate alternatives or take other applicable compliance actions, and selecting regulatory responses intended to prevent or manage potential adverse impacts to human health or the environment (California Code of Regulations, Title 22, Division 4.5, Chapter 55).

Problem

Certain chemicals used in consumer products may have hazard traits or environmental or toxicological endpoints of concern and may create potential exposures during manufacture, product use, recycling, treatment, or disposal. California policy analyses also identified limitations involving chemical hazard and exposure information, regulatory authority, and incentives for developing and adopting alternatives (Wilson et al. 2007).

State Regulatory Framework

California enacted green chemistry legislation in 2008 that authorized development of a regulatory process for identifying and evaluating chemicals in consumer products. The resulting SCP Program establishes procedures for identifying Candidate Chemicals and Priority Products, conducting alternatives analyses, and selecting regulatory responses. The program may address chemical substitution, material changes, product redesign, process changes, removal of a chemical or product from the California market, or other responses authorized by the regulations.

Safer Consumer Products Regulatory Framework

The SCP regulatory framework has four main parts (CA DTSC 2019a, 2019b):

1. **Candidate Chemicals:** A Candidate Chemical is a chemical that exhibits a hazard trait or environmental or toxicological endpoint and appears on one or more authoritative lists identified in the SCP Regulations, or that DTSC lists through rulemaking using the regulatory criteria. The informational Candidate Chemicals List changes as authoritative lists are updated, and DTSC may add chemicals or chemical groups through rulemaking. Inclusion on the Candidate Chemicals List does not by itself create a regulatory obligation. The list helps DTSC identify potential Chemicals of Concern when evaluating product-chemical combinations for possible listing as Priority Products.

2. **Priority Products:** A Priority Product is a consumer product that contains one or more Candidate Chemicals with the potential to contribute to significant or widespread adverse impacts and that has been formally listed in the California Code of Regulations through rulemaking. Regulatory obligations apply to the product-chemical combination identified in the Priority Product regulation, not to every use of the Candidate Chemical.
3. **Alternatives Analysis:** Once a product-chemical combination is listed as a Priority Product, responsible entities must comply with the applicable regulatory requirements. The principal pathway is an alternatives analysis that compares the Priority Product with potential alternatives using factors specified in the regulations. Alternatives may involve chemical substitution, material changes, product redesign, process changes, or other ways of providing the product's function. An alternatives analysis may be conducted by the manufacturer or by another entity acting on its behalf, such as a consortium, trade association, public-private partnership, or nonprofit organization.
4. **Regulatory Response:** Based on the alternatives analysis and other relevant information, CA DTSC may impose one or more regulatory responses to prevent or manage potential adverse impacts. Depending on the circumstances, responses may include information requirements, use restrictions, sales prohibitions, engineering or administrative controls, end-of-life management requirements, research requirements, or other measures authorized by the regulations. When sufficient alternatives information is already publicly available, CA DTSC may adopt regulatory responses as part of the Priority Product regulation rather than require the standard alternatives analysis process.

Program in Practice

Carpets and Rugs Containing Per- and Polyfluoroalkyl substances (PFAS): CA DTSC listed carpets and rugs containing PFAS as a Priority Product effective July 1, 2021. PFAS had been used in some carpets and rugs to provide stain, soil, oil, or water resistance. Responsible entities implemented product-removal or chemical-removal options rather than completing the standard alternatives analysis process. Subsequent compliance work found that products tested by CA DTSC generally did not contain the regulated PFAS above the applicable analytical thresholds. The example illustrates how a Priority Product listing can result in product reformulation or removal before completion of a formal alternatives analysis. It does not establish that every replacement product has a more favorable hazard, exposure, performance, or life-cycle profile (CA DTSC 2024)

Motor Vehicle Tires Containing 6PPD: CA DTSC listed motor vehicle tires containing 6PPD as a Priority Product effective October 1, 2023. 6PPD is used as an antidegradant to protect tire rubber from degradation caused by ozone, oxygen, heat, and mechanical stress. Its transformation product, 6PPD-quinone, has been associated with acute toxicity to certain aquatic species, including coho salmon. Responsible entities submitted a Preliminary, or Stage 1, alternatives analysis in 2024 and selected 21 potential alternatives for further evaluation. The next stage evaluates whether potential alternatives may be technically feasible and functionally acceptable and whether their hazard, exposure, and life-cycle characteristics support further consideration. Final alternatives analysis reports are due October 1, 2029 (CA DTSC 2023, 2026a).

Microplastics and Para-Phenylenediamine Derivatives: In 2026, DTSC added microplastics and para-phenylenediamine derivatives to the Candidate Chemicals List. Addition to the Candidate Chemicals List does not itself create a regulatory obligation but allows related chemicals to be considered within the SCP framework (CA DTSC 2026b)

Relationship to Product Life-Cycle Considerations

The SCP Program may affect several product life-cycle stages. Priority Product identification and alternatives analysis may influence chemical selection, product design, material selection, manufacturing, supplier decisions, product use, and end-of-life management. Regulatory responses may address product

information, use restrictions, sales, engineering or administrative controls, research, or end-of-life management.

The program is not itself a complete life-cycle assessment. Alternatives-analysis conclusions depend on the product function, alternatives considered, data, analytical methods, assumptions, uncertainty, and tradeoffs evaluated. A Priority Product listing or alternatives analysis requirement does not establish that every alternative has a more favorable hazard, exposure, performance, cost, or life-cycle profile.

Outcomes and Potential Impacts

- **Exposure:** Regulatory responses may reduce the use of or potential exposure to a Chemical of Concern in a Priority Product. The nature and magnitude of the effect depend on the regulatory response, compliance, product use, and alternative selected.
- **Alternatives Considerations:** Alternatives analysis requires comparison of potential alternatives using specified factors and can help identify whether a substitute could shift hazards or impacts. The process may reduce the likelihood of regrettable substitution but cannot guarantee that every selected alternative will be preferable under every condition.
- **Potential Downstream Implications:** Changes to chemical content or product design may affect releases, waste streams, recycling, treatment, disposal, and potential exposures. The extent of any reduction in contamination, cleanup costs, waste-management demands, or public-health impacts depends on the product, chemical, regulatory response, implementation, and alternative selected.
- **Product and Market Responses:** Priority Product listings, alternatives-analysis requirements, and regulatory responses may influence product formulation, material selection, supplier communication, product availability, and investment in potential alternatives. The magnitude and direction of these effects depend on the affected product, available alternatives, regulatory response, market conditions, and implementation schedule.

Relevant Green and Sustainable Chemistry Considerations

- **Pollution Prevention:** Regulatory responses may reduce or manage the use of a Chemical of Concern in a specified Priority Product before the chemical enters use, waste, recycling, treatment, or disposal streams.
- **Alternatives Assessment:** Responsible entities evaluate potential chemical, material, product-design, process, or functional alternatives using the factors specified in the SCP Regulations.
- **Hazard and Exposure Information:** Candidate Chemical and Priority Product decisions draw on hazard traits, environmental or toxicological endpoints, potential exposures, product uses, and other available information.
- **Performance and Function:** Alternatives analysis considers the function of the Chemical of Concern and the Priority Product, along with technical feasibility and product performance.
- **Life-Cycle Considerations:** Alternatives analysis may consider adverse impacts across relevant life-cycle segments, including manufacturing, use, end-of-life management, and environmental release.
- **Chemical-Class Considerations:** Listing or evaluating related chemicals as a class may help identify potential substitutes that warrant additional review, while recognizing that hazards, exposures, functions, and data may vary within a class.
- **Circularity Considerations**: Chemical content can affect whether products and materials are suitable for reuse, recycling, treatment, or disposal. Alternatives analysis and regulatory responses may consider end-of-life implications, but a change in chemical content does not by itself establish circularity or compatibility with recovery systems.

Relevance to Sustainable Systems

This case study illustrates a state framework that identifies Candidate Chemicals and Priority Products, requires alternatives analysis or other applicable compliance actions, and authorizes regulatory responses for specified product-chemical combinations. The framework incorporates hazard, potential exposure, product function, performance, alternatives, and life-cycle considerations that overlap with GSC concepts discussed in the Focus Sheet. The example does not establish that every Candidate Chemical presents the same level of concern, that every Priority Product requires the same regulatory response, or that every alternative is preferable across all relevant attributes.

References

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