GREEN CHEMISTRY &
COMMERCE COUNCIL

The GC3 Blueprint of Green Chemistry Opportunities for a Circular Economy

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ACKNOWLEDGEMENTS

This report is written by the Green Chemistry & Commerce Council (GC3). Supported by the Forsythia Foundation, The GC3 Blueprint of Green Chemistry Opportunities for a Circular Economy report discusses how green chemistry can support and amplify the circular economy goals, as developed by the Ellen MacArthur Foundation, to help companies throughout the industrial value chain harness the power of green chemistry to meet the growing need for a more sustainable economy.

The GC3 would like to thank all of its members, whose direct and indirect contributions led to the development of this report. Member leadership in GC3 initiatives, as well as in their own organizational circular economy approaches provided inspiration for this report.

ABOUT THE ORGANIZATIONS

GC3
GREEN CHEMISTRY & COMMERCE COUNCIL

Green Chemistry & Commerce Council (GC3)

Started in 2005, the Green Chemistry & Commerce Council (GC3) is a business-to-business collaborative that drives the commercial adoption of green chemistry by catalyzing and guiding action across all industries, sectors and supply chains. Over 125 organizations are members of the GC3. For more information, visit www.greenchemistryandcommerce.org.

FORSYTHIA

Forsythia Foundation

Forsythia Foundation promotes healthier people and environments by reducing harmful chemicals in our lives. Forsythia Foundation believes in putting the full spectrum of philanthropic capital — time, networks, grants, and investments — to work. For more about Forsythia, visit www.forsythiafdn.org.

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Introduction

The Green Chemistry & Commerce Council (GC3) is a multi-stakeholder collaborative that drives the commercial adoption of green chemistry by catalyzing and guiding action across all industries, sectors and supply chains. The GC3 works strategically to 1) develop and promote tools, policies and business practices to drive green chemistry throughout supply chains, 2) foster collaboration among businesses, government, non-governmental organizations, and academic researchers, and 3) identify and leverage enablers of green chemistry adoption.

GC3 members are increasingly challenged to achieve multiple sustainability objectives, such as those outlined in the United Nations (UN) Sustainable Development Goals (SDGs)[1], including carbon reduction[2] and circularity[3]. There are increasing policy, marketplace, and investor demands for more circular materials and products. Green chemistry and the circular economy share the fundamental goals of shifting towards an economy that uses resources efficiently and safely, thereby reducing waste and protecting human health and the environment. Both start with a fundamental rethinking of how to design chemicals, materials, products, and processes to be safer and more sustainable.

This report explores the synergies between green chemistry principles and the circular economy framework. Each has the opportunity to enable and optimize the other, and this report focuses on the innovations needed to realize those opportunities. The Blueprint was written in part to support companies and others as they make design, sourcing, and manufacturing decisions about chemicals, materials, and products that can advance both circular economy and green and sustainable chemistry goals.

This report explores the synergies between green chemistry principles and the circular economy framework. Each has the opportunity to enable and optimize the other, and this report focuses on the innovations needed to realize those opportunities.

The ultimate objective of this Blueprint is to understand how the two concepts can work together to accelerate the commercialization of safer, more sustainable, materials and products across sectors and value chains. The Blueprint is designed as a starting point for on-going dialogue on how to co-optimize the circularity, safety, and sustainability of chemicals, materials, and products, while minimizing potential trade-offs. There are likely to be differences of opinion with regards to balancing potential trade-offs or how particular technologies and actions support or could detract from the mutual goals of green chemistry and the circular economy depending on which sector or where in the supply chain companies sit. As such, this document should be seen as a Version 1.0, to be updated as a result of evolving feedback and understanding. The GC3 hopes it will provoke thought, promote discussion, and invite conversation.

Fundamentals of the Circular Economy

Over the last decade, the concept of a "circular economy" has gained considerable momentum, advanced by the efforts of the Ellen MacArthur Foundation, founded in 2009, and others. Foundational elements of the circular economy concept are not new—having being introduced in the 1990s—and include different product design, service, and end-of-life models to achieve reduction of waste, longevity of products, and regeneration of natural materials. The circular economy looks beyond the current linear economic system—that is, an extractive industrial model of take-make-use-waste—to gradually decouple economic activity from the consumption of finite resources, ultimately designing waste out of the system. The concept has been brought to the forefront in recent years by advocates in NGOs, governments, and businesses as an approach that can address many sustainability concerns, ranging from plastics waste to non-renewable resource use.

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1 UN General Assembly. (2015). Transforming Our World: The 2030 Agenda for Sustainable Development. *Division for Sustainable Development Goals: New York, NY, USA.*

2 Goal 13: Climate action, UN General Assembly. (2015). Transforming Our World: The 2030 Agenda for Sustainable Development. *Division for Sustainable Development Goals: New York, NY, USA.*

3 Goal 12: Responsible consumption and production, UN General Assembly. (2015). Transforming Our World: The 2030 Agenda for Sustainable Development. *Division for Sustainable Development Goals: New York, NY, USA.*

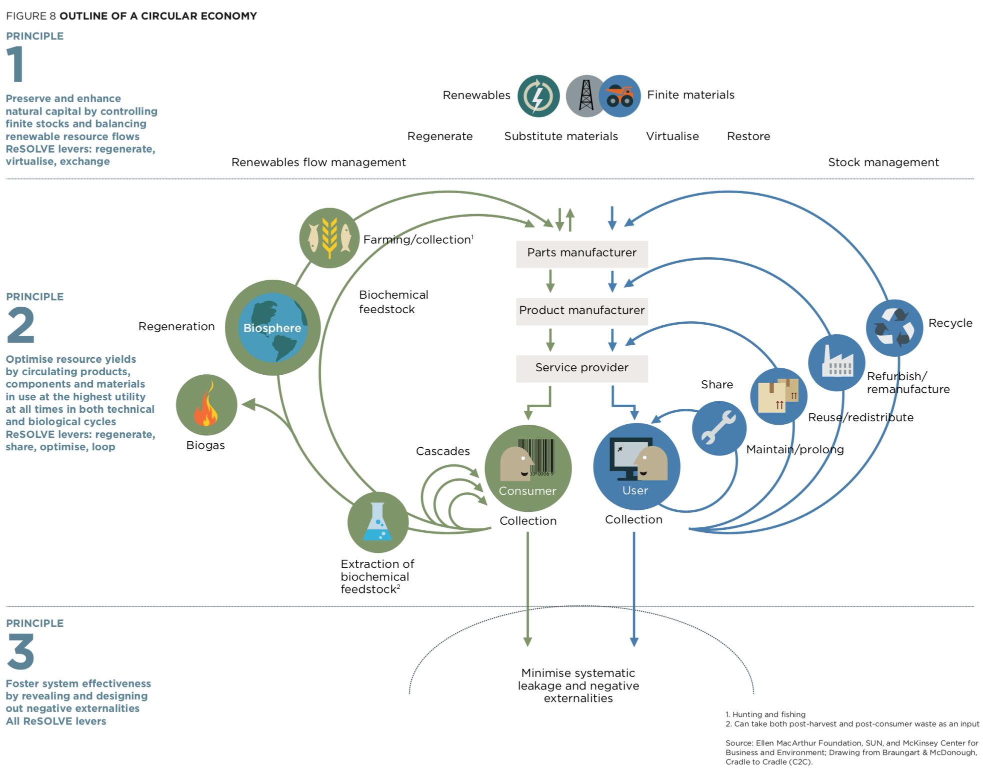


Figure 1: The Ellen MacArthur Foundation Circular Economy Systems Diagram[4]

Transitioning to a circular economy not only reduces the negative impacts of the linear economy, it also represents a systemic shift that builds long-term ecosystem resilience, generates business and economic opportunities, and provides environmental and societal benefits.

According to the Ellen MacArthur Foundation, a circular economy is based on three key principles: **i) designing out waste and pollution; ii) keeping products and materials in use; and iii) regenerating natural systems (i.e. avoiding the use of non-renewable resources and preserving or enhancing renewable ones).** For the purposes of this report, the terms "circular economy" and "circularity" are used interchangeably to refer to chemicals, materials, and products that advance the circular economy principles.

The Foundation's "butterfly diagram," as shown, left, in Figure 1, illustrates possible material pathways for the continuous flow of technical and biological materials through value circles, with each loop representing an alternative for extending use. In this report, these material pathways serve as the basis for discussion outlining the green chemistry opportunities to enable these flows.[4]

The butterfly diagram illustrates opportunities to increase material productivity through new business models and incentives to design differently. For instance, the 'power of the inner circle' relates to the minimization of material usage, where the smaller interior circles, representing practices such as 'share' and 'maintain/prolong,' embody scenarios where less of the product has to be changed to continue use, as compared to end-of-life pathways, such as refurbishment, remanufacturing, and recycling. This circle structure replicates the waste minimization hierarchy, commonly described in pollution prevention.[5] The benefit of the inner circle pathways is that fewer resources are required to obtain continued value from products, resulting in fewer associated impacts. Throughout this report, the Ellen MacArthur Foundation principles and butterfly approach provide the framework for understanding connections to green chemistry.

4 Ellen MacArthur Foundation (2015). Growth within: a Circular Economy Vision for a Competitive Europe, https://www.ellenmacarthurfoundation.org/publications/growth-within-a-circular-economy-vision-for-a-competitive-europe

5 Bourguignon D (2017). Circular economy package. Four legislative proposals on waste, report for European Parliamentary Research Service. Brussels: European Parliamentary Research Service (http://www.europarl.europa.eu/RegData/etudes/BRIE/2017/599288/EPRS_BRI(2017)599288_EN.pdf).

Unintended Consequences: Recirculation of Toxic Materials in Circular Economy

The benefits of a circular economy have been well-documented.[6, 7, 8, 9, 10] Strategies to "keep products in use" for longer, including strategies to reuse, repair, refurbish and then ultimately recycle, have the potential to significantly minimize waste and resource use. However, there are increasing concerns about the recirculation of potentially toxic materials in a circular economy, increasing the chances for human and environmental exposure. For example, polybrominated diphenyl ether (PBDE) flame retardants have been found in recycled foam carpet backing, potentially increasing (dispersing) exposure.[11] A number of analyses and policy proposals for implementing circular economy approaches highlight the need for safer, more sustainable chemicals as a key prerequisite, including:

- The British NGO ChemTrust[12] surveyed businesses, NGOs, and trade organizations to address the interface between chemical, product, and waste legislation in the EU.[13] The work examined concerns and options for defining and tracking of substances of concern.
- Swedish NGO ChemSec's report on business opportunities in a circular economy states that "designing and manufacturing products to be recycled is great. But there is one piece missing in the circular economy debate—hazardous chemicals. Without proper attention to chemicals, the circular economy will never work."[14]
- A report by Google and the Ellen MacArthur Foundation notes that "if we are going to keep materials flowing in commerce longer, we have to design them to be safe for human and environmental systems, because we can't change the chemistry of products once we put them out in the world." It adds "we must radically enable and then accelerate safer material innovation if we want to realize a future where materials cycle perpetually in closed loop systems without toxifying people and the planet."[15]

Strategies to "keep products in use" for longer, including strategies to reuse, repair, refurbish and then ultimately recycle, have the potential to significantly minimize waste and resource use.

6 Ellen MacArthur Foundation. (n.d.). Case Studies. https://www.ellenmacarthurfoundation.org/case-studies/business

7 Chavin, S., & Jeffries, N. (2017, Nov 2). Six circular economy case studies from Brazil. Circulate. Ellen MacArthur Foundation. https://medium.com/circulatenews/six-circular-economy-case-studies-from-brazil-3d7a9656da26

8 Jeffries, N. (2017, September 11). Six circular economy case studies from the USA. Circulate. Ellen MacArthur Foundation. https://medium.com/circulatenews/six-circular-economy-case-studies-from-the-usa-8d9258bd340f

9 Jeffries, N. (2018, February 8). A circular economy for food: 5 case studies. Circulate. Ellen MacArthur Foundation. https://medium.com/circulatenews/a-circular-economy-for-food-5-case-studies-5722728c9f1e

10 Jeffries, N. (2018, July 16). Circular economy in China: six examples. Circulate. Ellen MacArthur Foundation. https://medium.com/circulatenews/circular-economy-in-china-six-examples-2709982763f2

11 International Joint Commission. (2017). *Addressing Polybrominated Diphenyl Ethers in the Great Lakes Basin: Searching for Solutions to Key Challenges.* Great Lakes Water Quality Board, Windsor, Ontario, Canada. International Joint Commission (IJC) Digital Archive.

12 See also ChemTrust policy briefing Circular Economy and Chemicals: Creating a clean and sustainable circle (2015). https://chemtrust.org/wp-content/uploads/chemtrust-circulareconomy-aug2015.pdf

13 European Commission. (2019). Summary Report of the Public Consultation conducted by the European Commission based on the main issues identified in the Commission's Communication on the interface between chemical, product and waste legislation (COM(2018) 32 final). Retrieved from https://ec.europa.eu/info/sites/info/files/summary-report-public-consultation-chemical-product-waste-legilsation.pdf

14 The International Chemical Secretariat (ChemSec). (2019). The missing piece: Chemicals in Circular Economy. [online] The International Chemical Secretariat, p.5. Retrieved from https://chemsec.org/app/uploads/2019/03/The-missing-piece_190313.pdf

15 Ellen MacArthur Foundation and Google. (2018). The Role of Safe Chemistry and Healthy Materials in Unlocking the Circular Economy. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/The-Role-of-Safe-Chemistry-and-Healthy-Materials-in-Unlocking-the-Circular-Economy.pdf

- At least two of the initiatives in the European Union's Circular Economy Action Plan aim at addressing the interface between chemicals, products, and waste legislation, reducing the presence and improving the tracking of chemicals of concern in products, and developing an improved knowledge base and support to small and medium-sized enterprises for the substitution of hazardous substances of very high concern.[16]
- The European Commission's 2019 report, *A Circular Economy for Plastics,* discusses circular approaches to address the impacts of plastics and their underlying chemistries, including suggestions for novel sources, designs and business models for plastics.[17]
- Presentations and stakeholder recommendations from the June 2019, EU Chemicals Policy 2030 stakeholder conference, convened by the European Commission and Ministry for Environment and Food of Denmark, noted the need for "a safe, transparent and sustainable circular economy, with an emphasis on the design of high quality and safe products that maximize circularity."[18]

Given the increasing awareness of the potential impacts of hazardous chemicals on circular systems, this report examines the opportunities for green chemistry to minimize the potential impact of hazardous chemicals recirculating in the system.

Since chemicals are the building blocks for all materials and products, the selection of safer, more sustainable chemistries can have a significant impact on the product life cycle, including the potential sustainability of these materials—manufacture, use, reuse and recycling, and ultimately its end of life.

The Role of Green Chemistry in the Circular Economy

Green chemistry has been defined as "the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances throughout the life cycle of products."[19] The 12 principles of green chemistry expand beyond this definition to include elements such as energy efficiency, atom efficiency, waste reduction, and degradation, providing an essential toolbox for sustainable chemical design and synthesis that prevents pollution at the molecular level. Since chemicals are the building blocks for all materials and products, the selection of safer, more sustainable chemistries can have a significant impact on the product life cycle, including the potential sustainability of these materials—manufacture, use, reuse and recycling, and ultimately its end of life. Consequently, careful chemistry decisions are fundamental to optimize materials and products for a sustainable circular economy.

Given its focus on molecular synthesis—for the design of new materials and products—green chemistry can play an essential role in safe and sustainable circularity in two particular areas: 1) designing safer, less toxic chemicals and chemical processes; and 2) use of renewable feedstocks. However, the role of green chemistry innovation in supporting other aspects of circularly, where products and materials are already created, for example remanufacturing, recycling, or repair, is perhaps not as intuitive. It is clear that when green chemistry and circular economy principles are combined, they can greatly expand the scope of approaches and techniques for enabling safe and sustainable solutions. Yet, while creating an entire economy based on

16 European Commission. (2020). A New Circular Economy Action Plan for a Cleaner and More Competitive Europe. Retrieved from https://ec.europa.eu/environment/circular-economy/index_en.htm

17 European Commission. (2019). A Circular Economy for Plastics: Insights from Research and Innovation to Inform Policy and Funding Decisions. Retrieved from https://op.europa.eu/en/publication-detail/-/publication/33251cf9-3b0b-11e9-8d04-01aa75ed71a1/language-en/format-PDF/source-87705298

18 European Commission and Ministry for Environment and Food of Denmark. (2019). EU Chemicals Policy 2030 Building on the Past, Moving to the Future. Retrieved from https://euchemicalspolicy2030.teamwork.fr/docs/report.pdf

19 See U.S. Environmental Protection Agency. Basics of Green Chemistry https://www.epa.gov/greenchemistry/basics-green-chemistry

renewable, circular, green chemistry solutions is an important vision for the future, it may not be fully feasible at this juncture. Renewable feedstocks and the green chemistries built from them do not yet exist at scale and likely will not for some time.

When the means to create circular systems do not exist, then a path to the circular economy must be developed and additional solutions are needed in the interim. For example, recycling existing materials as feedstocks for creating new materials may be preferable to creating them out of new feedstocks, to reduce energy, waste, and costs in the short to medium terms. In these cases, finding ways to dilute, encapsulate, or otherwise detoxify potentially toxic or persistent/bioaccumulative additives or building blocks will be needed to minimize potential trade-offs and protect the health of those who may be impacted. The discussion below explores potential areas of synergy between the principles of green chemistry and the circular economy that enable the co-optimized goals of both a "detoxification" and "dematerialization" of the economy (see Figure 2 which explores the intersection of green chemistry and circular economy principles).

FIGURE 2: The Relevance of the 12 Principles of Green Chemistry (GC) to Address the Three Principles of the Circular Economy (CE)

		Regenerating natural systems	Keeping products + materials in use	Designing out waste + pollution
1	**Waste prevention:** Prevent chemical substance waste instead of treating it or cleaning it up after it is formed.	■	✔	✔
2	**Atom economy:** Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.	■	✓	✓
3	**Less Hazardous Chemical Syntheses:** Synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.	■	✓	✔
4	**Designing safer chemicals:** Chemical products should be designed to preserve their efficacy of function while reducing toxicity.	✔	✔	✔
5	**Safer solvents and auxiliaries:** The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary and innocuous when used.	✔	✔	✔
6	**Design for energy efficiency:** Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.	■	✓	✓
7	**Use of renewable feedstocks:** A raw material or feedstock should be renewable rather than depleting.	✔	■	✓
8	**Reduce derivatives:** Unnecessary derivatization (blocking groups, protection/deprotection, temporary modification of physical/chemical processes) should be avoided.	■	✔	✔
9	**Catalysis:** Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.	✔	✔	✔
10	**Design for degradation:** Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products.	✔	■	✔
11	**Real-time analysis for pollution prevention:** Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.	■	✔	✔
12	**Inherently safer chemistry for accident prevention:** Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.	✓	✓	✔

LEGEND

✔	GC principle is highly relevant to CE principle
✓	GC principle potentially but not necessarily relevant to CE principle
■	Relevance of GC principles to CE is less clear

Given the potential for "leakages" of chemicals through their manufacturing, use, and reuse, designing benign chemicals at the outset can enable safe circularity throughout the various phases of a product's life.

Benign Chemicals Are Critical for Circularity

Designing benign chemicals and chemical products, green chemistry principle (GC principle) 4, in particular, is a foundational need to advance all three circular economy principles **(designing out waste, keeping materials in use, and regenerating natural systems)** and is the focus of much policy and NGO attention. With a goal of circularity to continue utilizing what is typically discarded, hazardous chemicals are increasingly problematic feedstocks. For instance, when the life of finite materials is extended through reuse, the risk associated with chemicals of concern could increase with the associated intensified possibility of exposure. Additionally, if not thoughtfully tracked and managed, small quantities of potentially hazardous chemicals in a product can amplify the potential for exposure as they are reprocessed for materials over multiple cycles. Given the potential for "leakages" of chemicals through their manufacturing, use, and reuse, designing benign chemicals at the outset can enable safe circularity throughout the various phases of a product's life.

Additional GC principles focused on the safety of the synthesis process, including less hazardous chemical syntheses—GC principle 3—and safer solvents and auxiliaries—GC principle 5—can reduce the risk of residual hazardous substances (process chemistries or byproducts) being incorporated into new or recycled materials and products and potentially exposing humans and ecosystems, keeping materials in use and reducing pollution and waste. Several GC principles pertaining to the safety aspects of the synthesis or resynthesis process—such as GC principle 8: reduce derivatives, GC principle 11: real-time analysis for pollution prevention, and GC principle 12: inherently safer chemistry for accident prevention—center on minimizing the generation of hazardous waste and potential for chemical accidents that can occur during manufacturing, recycling, and remanufacturing operations.

Green Chemistry Can Enable the Regeneration of Natural Systems

The role of green chemistry in developing innovations needed for circularity extends beyond benign chemicals. To achieve the regeneration of natural systems requires inputs and outputs of natural capital. GC principle 7 calls for the use of renewable raw materials and feedstocks, rather than depleting finite resources. Green chemistry can enable the use of feedstocks that are sourced from sustainably harvested natural resources, as well as new sources, such as waste carbon dioxide and methane derived from biochemical decomposition. Such feedstocks have the potential to be manufactured in ways that reduce the potential for chemical accidents and generation of hazardous waste. Also needed for circular renewable materials are chemicals that can degrade in a safe way and regenerate natural systems. GC principle 10 calls for chemicals that do not persist in the environment and break down into innocuous degradation products. This is particularly important for formulated products intentionally released into the environment, such as cleaners and cosmetic products (see Box 2 on Consumable Products, page 19). Discussions about "regenerative products" are evolving and some chemistries, especially those derived from renewable feedstocks, such as renewable solvents—elevated by GC principle 5[20, 21]—and biocatalysis—inspired by GC principle 9[22]—may serve a role in supporting regeneration of natural systems.

Green Chemistry Can Enable Keeping Products & Materials in Use

Benign chemicals and synthesis processes are important to keeping products and materials in use and maximizing the potential for reuse, without the need to manage potential hazards and exposures for future applications. Additionally, designing the synthesis process with the intended final product in

[20] Gu, Y., & Jérôme, F. (2013). Bio-based solvents: an emerging generation of fluids for the design of eco-efficient processes in catalysis and organic chemistry. *Chemical Society Reviews,* 42(24), 9550-9570.

[21] Clarke, C. J., Tu, W. C., Levers, O., Brohl, A., & Hallett, J. P. (2018). Green and sustainable solvents in chemical processes. *Chemical Reviews,* 118(2), 747-800.

[22] Sheldon, R. A. (1997). Catalysis and pollution prevention. Chemistry and Industry, (1), 12-15.

mind, without unnecessary waste-generating steps, as called for in GC principles 1, 8, 11, keeps all the material in use for its intended purpose. Solvents can be recovered and reused when made safer with GC principle 5.[23] GC principle 11, analytical methodologies for real-time, in-process monitoring and control, prior to the formation of hazardous substances can also play an important role in keeping materials circulating in the economy (coupled with new service models, such as chemical leasing). Biocatalytic conversion, encouraged by GC principle 9, provides an opportunity to recycle plastic waste.[24]

As societies transition away from the current practices of linear systems to develop pathways to the circular economy, solutions are needed to address existing challenges and make progress in utilizing existing stocks of materials already in the economy in the interim.

Green Chemistry Can Enable Designing out Waste & Pollution

GC principle 1 calls for waste prevention, specifically the designing out of chemical substance waste, instead of treating it or cleaning it up after it is formed. Additionally, GC principle 4 calling for benign chemicals, GC principles 3, 5, 8, 9 and 12, relating to sustainable synthesis techniques, and GC principle 11, pertaining to real-time analytic methods, mitigate the likelihood of "leakages" of waste or other emissions and their impacts in the system. Safer solvent selection, under principle 5, can address waste in two ways: by using valorized organic wastes as a primary raw material source for solvents and by selecting solvents that minimize waste generation of chemical processes.[21] The use of heterogeneous catalysis, homogeneous catalysis, organocatalysis, and biocatalysis can reduce the waste caused by stoichiometric reagents in organic synthesis, as part of GC principle 9.[22, 25, 26]

Green Chemistry in the Interim: Transitioning to a Circular Economy

The circular economy is largely built upon the premise that sustainability decisions are ideally made during the design phase, when resource use and impacts can best be reduced. However, as societies transition away from the current practices of linear systems to develop pathways to the circular economy, solutions are needed to address existing challenges and make progress in utilizing existing stocks of materials already in the economy in the interim. Current options to advance towards the circular economy can present tensions that green chemistry may help resolve but they may also involve trade-offs between sub-optimal solutions until ideal ones can be fully developed.

While reducing the health and environmental impacts of chemicals and chemical processes is key to all facets of circularity, potentially hazardous substances currently used in materials and products may be there to perform an important function that is critical to circularity, such as anti-corrosive or stain resistant coatings to improve durability, or certain potentially hazardous metals in catalysis. These instances provide clear challenges for the development of green chemistry solutions, particularly in cases where there is potential for leakage in the system or where hazards and exposures are not easily and safely managed. Tensions may also exist when considering chemical design and selection for single uses versus multiple uses of a material or when recycled materials are used as a starting point; however, when atom economy is considered from a system perspective, where all inputs and outputs through the product life cycle are considered, this can be better optimized.

When materials are kept in circulation through sharing, maintaining, prolonging, reusing, redistributing, refurbishing, remanufacturing, and recycling, the inputs for and impacts of those materials, such as waste generation, energy use, and natural resource extraction, can be reduced as they are amortized across multiple uses. This is particularly true when the exposure potential of a hazardous

[23] Clark, J. H., Farmer, T. J., Herrero-Davila, L., & Sherwood, J. (2016). Circular economy design considerations for research and process development in the chemical sciences. *Green Chemistry,* 18(14), 3914-3934.

[24] Editors, Nature Catalysis. (2019). Plastic upcycling. *Nature Catalysis*, 2, 945–946.

[25] Sheldon, R. A., Arends, I., & Hanefeld, U. (2007). *Green Chemistry and Catalysis.* John Wiley & Sons.

[26] Sheldon, R. A., & Woodley, J. M. (2018). Role of biocatalysis in sustainable chemistry. *Chemical Reviews,* 118(2), 801-838.

The GC3 Blueprint of Green Chemistry Opportunities for a Circular Economy is a framework created to support company, designer, and government decision-making regarding chemicals and materials development and selection and product design, in the transition towards a safe and sustainable circular economy.

starting material is low but can result in trade-offs when that material is recycled in the economy. There may be opportunities to safely recycle some hazardous chemicals in the economy if there is little to no "leakage;" however, this often requires significant process and product control, and may also require additive chemistries to result in technically viable materials over multiple uses. Yet, there also may be opportunities to "detoxify" or break down hazardous chemicals or materials into more benign molecules for recycling or disposal (see Box 3 on Chemical Recycling, page 32).

The GC3 Blueprint of Green Chemistry Opportunities for a Circular Economy

Chemistry plays a critical role in facilitating the continued sustainable cycling of resources, transitioning from linear to circular product and material use. It can support implementable actions that enable the loops envisioned in the Ellen MacArthur Foundation butterfly diagram (Circular Economy Loops). Specifically, green chemistry can help to ensure that any chemistry innovation that is adopted for the circular economy minimizes unintended negative impacts.

The GC3 Blueprint of Green Chemistry Opportunities for a Circular Economy is a framework created to support company, designer, and government decision-making regarding chemicals and materials development and selection and product design, in the transition towards a safe and sustainable circular economy. It identifies a set of chemistry opportunities that can enable the Circular Economy loops, as developed by the Ellen MacArthur Foundation. Included with each opportunity is a description of the opportunity, its relevance to the circular economy, and a discussion of its potential nexus with green chemistry. Questions are provided to help companies and others engage internal and supply chain stakeholders in identifying needs and opportunities along the product value chain to co-optimize green chemistry and circularity goals. These questions can help identify targeted green chemistry innovation needs to support circularity in a particular company or industry as well as best practices and potential approaches for meeting those needs. These aspects provide a flexible approach that allows for a broad group of industries and other stakeholders to map and assess current research and development and sourcing activities. Ultimately, this engagement can identify opportunities for innovation.

Identifying Green Chemistry Opportunities to Support a Circular Economy

For the Blueprint, the GC3 identified a set of chemistry needs that, if met, could help guide actionable steps to drive innovation in support of circularity. The objective was to understand the landscape around the enabling role of chemistry, and specifically green chemistry, in furthering the aims of circularity. The chemistry needs were identified based on a survey and review of GC3 member technology needs, input from circular economy and green chemistry experts, and an analysis of existing circular economy design practices. Secondary research on innovation needs and chemistry as an enabler for circularity was conducted to understand gaps, challenges, and barriers at the intersection of chemistry and circularity. From this assessment, it is possible to identify where key green chemistry innovation opportunities exist to enhance the circular economy. The process of identifying needs is summarized in the Appendix.

The research effort on chemistry and material needs identified eight categories of opportunities for green chemistry innovation that could support circularity. To create a framework for understanding the potential value of green chemistry in enabling circularity in each of these areas of opportunity, these were mapped to the circular economy loops (which were combined for renewable and finite materials) in the following manner: 1) biochemical feedstocks; 2) share; 3) maintain/prolong/reuse/redistribute; 4) refurbish/remanufacture. The categories of opportunities and their mapping to the loops are described below and displayed in Figure 3.

Some of these areas of opportunity are relevant to the principles of green chemistry, as outlined in Figure 2. The categories of opportunities where green chemistry is clearly a necessary requirement for circularity are denoted with a green numbered circle in Figure 3. For other categories, specifically those that are within the circular economy loops associated with the principle to "keep products and materials in use," the direct connections to the green chemistry principles are not immediately obvious, though green chemistry solutions can drive the particular chemistry and materials innovation needs for that category. Importantly, the opportunities can be seen as cumulative in nature. For example, while 'safety' is a critical need for any product destined for remanufacturing, so is 'durability'.

The approach to identifying and categorizing opportunities attempts to roughly juxtapose the circular economy loops and the molecular level design principle focus of green chemistry. There is no clear 1-to-1 relationships between circular economy loops and green chemistry principles (for example, that "refurbish" belongs to green chemistry principle x). It is easier to view principles more as design principles (the input) on the one hand and the loops as desired systemic outcomes (the output) of any design. While the categorization may appear complex, as greater discussion and understanding of the interconnections between green chemistry and circularity evolve, simpler ways to describe the connections will become apparent.

Eight Categories of Green Chemistry Opportunities to Support a Circular Economy

Biochemical Feedstocks

1. **New Pathways.** Developing efficient pathways for making essential platform chemicals, including alternative processes that do not rely on non-renewable fossil feedstocks, in a way that preserves biodiversity and natural capital

Share

2. **Safety.** Eliminating known chemical hazards that would otherwise be amplified with intensified material utilization

Maintain/ Prolong/ Reuse/ Redistribute

3. **Durability.** Ensuring materials and components retain their properties and are not fatigued over prolonged and multiple use cycles
4. **Integrity.** Keeping chemicals in their designated places and functionalities without migrating over time

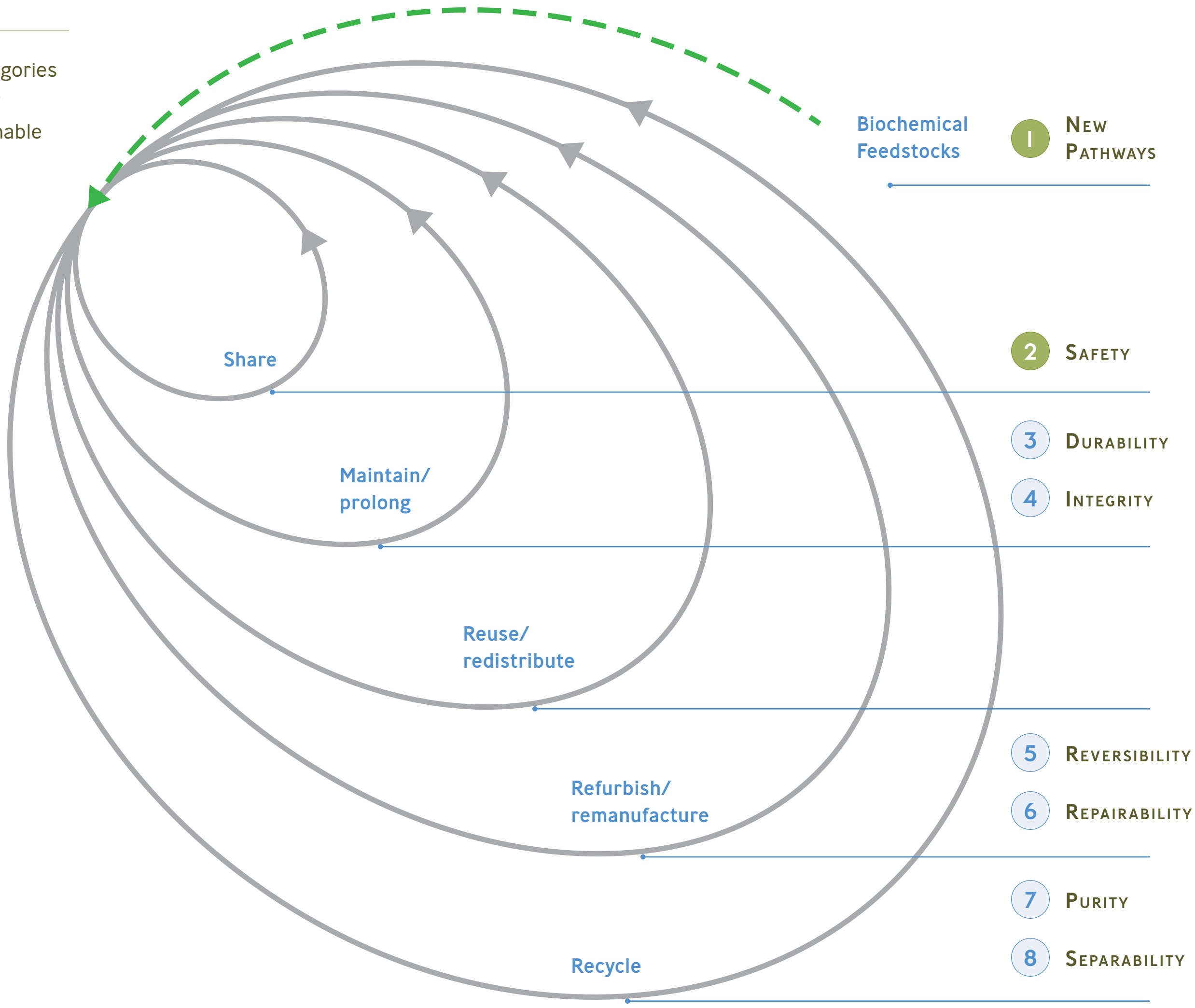
Refurbish/ Remanufacture

5. **Reversibility.** Enabling parts and components to come apart without excessive use of physical or chemical force, while maintaining performance
6. **Repairability.** Building up worn or fatigued materials in an additive way without having to discard large volumes

Recycle

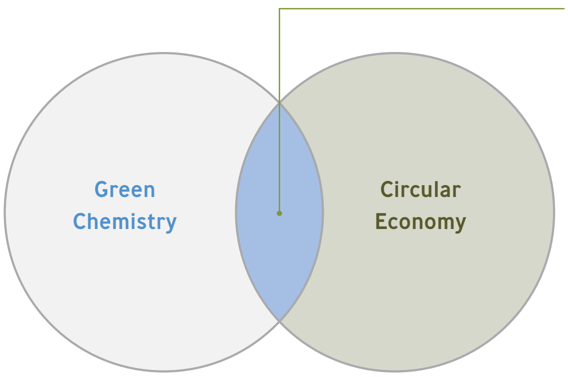
7. **Purity.** Removing unwanted additives and contaminants to make a pure, functional, consistent, and compatible secondary raw material, or make simpler materials requiring less mixing or additives
8. **Separability.** If composite materials are used, separating key components from each other for further use

FIGURE 3: GC3 Categories of Green Chemistry Opportunities to Enable a Circular Economy



The eight categories of green chemistry opportunities, organized by the loops, are described in further detail below. For each, its relevance to the circular economy and potential nexus with green chemistry principles is discussed. Questions are provided to encourage thinking to progress towards innovation based on what is technologically available today (i.e. the current state of the market—are green chemistry solutions available or do they need to be developed), a company's current practices, and opportunities for incremental improvement and innovation.

I. GREEN CHEMISTRY OPPORTUNITIES IN NEW PATHWAYS. Developing efficient pathways for making essential platform chemicals, including alternative processes that do not rely on non-renewable fossil feedstocks, in a way that preserves biodiversity and natural capital



The Intersection of Green Chemistry and Circular Economy: New Pathways

- The development of new efficient pathways for renewably sourced essential platform chemicals
- The development of new chemical and material end products sourced from renewably sourced essential platform chemicals in a way that preserves biodiversity and natural capital
- The development of potentially safer, more sustainable, chemicals and products
- The potential minimization for accidents through safer feedstocks

Key Questions

Current State of the Market

- Do sources of diverse, renewable feedstocks exist that suit performance needs and are available in sufficient quantity?
- Are the biodiversity and natural capital impacts of available renewable feedstocks known and, if so, are they minimized?

Establishing Your Baseline

- Does your company offer or utilize platform chemicals, or specialty chemicals, derived from renewable sources?
- If your company offers or utilizes renewable feedstocks, or specialty chemicals derived from such sources, has it assessed their impact on biodiversity and natural capital? Do these include considerations of growing and harvesting, including water quality, erosion, greenhouse gas production?
- Does your company consider the biological services your biofeedstocks are providing, such as carbon sequestration, flood control, erosion control, excess nutrient processing?

Opportunities for Growth

- Is your company working to increase its offerings or use of products from existing alternative platform chemicals?

- Could your company take actions to send demand signals to help address existing barriers around the price, performance, or scale of adopting renewable feedstocks with an improved biodiversity and natural capital profile?
- Could your company collaborate with others in your sector or supply chain, or other stakeholders, to increase your leverage to help address such barriers?
- Has your company evaluated opportunities to improve the biodiversity and natural capital impacts of the renewable feedstocks it offers or utilizes?
- Could your company change business practices to help support renewable resource regeneration?
- Could your company increase its efforts to educate consumers regarding the importance of biodiversity and natural capital preservation in chemicals and materials?

By using chemicals made from renewable sources, such as plants and agricultural waste, rather than other equivalent chemicals originating from petrochemical sources, dependence on and impacts from fossil carbons (from oil, coal, and gas) will diminish.

Opportunities for Innovation

- Could your company increase access to renewable feedstocks by engaging with stakeholders at different levels of the supply chain and across sectors?
- Is your company actively engaged with its supply chain partners to either develop novel renewable feedstocks with an improved biodiversity and natural capital profile or to improve such impacts for existing renewable feedstocks?
- Is your company actively engaged with your supply chain partners or other stakeholders to develop novel platform chemicals or processing technologies or products created from such chemicals?
- Is your company working towards creating metrics and measures of success to support the preservation of biodiversity and natural capital?

Considerations: One of the principles of green chemistry is the use of renewable raw materials and feedstocks. By using chemicals made from renewable sources, such as plants and agricultural waste, rather than other equivalent chemicals originating from petrochemical sources, dependence on and impacts from fossil carbons (from oil, coal, and gas) will diminish.[27] While one of the primary goals of the circular economy model is to keep materials in use as long as possible, recirculating such materials with 100% efficiency is often not possible. As a result, even highly optimized circular systems will eventually require new feedstock to replace material losses. While green chemistry provides insights into the needs for improved biorefining and renewable pathways, the circular economy provides an outlook emphasizing sustainable agricultural practices that regenerate the system.

For fossil carbon feedstocks, substitution with renewable feedstocks is one means to offset the impacts of sourcing virgin feedstock. Biomass can reduce the need to exploit finite resources and, given the intake of carbon dioxide during plant growth, it also has the potential for lower human health and greenhouse gas impacts than fossil carbon alternatives.[28] Biomass conversion can create new chemical building blocks (C1-Cn compounds) and end products (e.g. ethanol and methanol) as well as new materials. [29]

[27] Erythropel, H. C., Zimmerman, J. B., de Winter, T. M., Petitjean, L., Melnikov, F., Lam, C. H.,… & Pincus, L. N. (2018). The Green ChemisTREE: 20 years after taking root with the 12 principles. *Green Chemistry,* 20(9), 1929-1961.

[28] Toensmeier, E., & Blake, A. (2017). Industrial Perennial Crops for a Post-Petroleum Materials Economy.

[29] Brar, S. K., Sarma, S. J., & Pakshirajan, K. (2016). *Platform chemical biorefinery: future green chemistry.* Elsevier.

Despite the positive impacts that can be derived from renewable feedstocks, they can also have potential negative externalities associated with their sourcing that must be considered and mitigated.

A platform chemical is an intermediate molecule, with a structure that is a building block from which fine and specialty chemicals can be converted.[30, 31] While it is technically feasible to create such chemicals from renewable raw materials, it is currently not always commercially feasible, because current processes are inefficient or expensive and end products have insufficient purity.[32] To be successful, bio-based platform chemicals should be produced, at scale, at a competitive cost, and be inserted within a complete innovation ecosystem that is able to create value. A key consideration for developing alternative pathways for making essential platform chemicals is how to improve material conversion and processing efficiency to make new pathways competitive. There is a need for green chemistry in both the areas of biocatalysis and separations to address purity challenges.[33] New research in synthetic biology may provide great opportunities for new chemistries and synthesis pathways that minimize the use of non-renewable resources.

Many GC3 member companies create chemicals or products using chemicals sourced from renewable raw materials. Companies that are commercializing renewable chemical processes and bio-based products can be found in a Biotechnology Innovation Organization (BIO– a biotechnology trade association) 2018 report.[34] Additionally, venture capital fund Safer Made provides examples of organizations creating bio-based chemicals and materials in their food packaging[35] and textile/apparel[36] reports.

Bio-based plastics currently make up a small, but growing, portion of the overall plastics market[37] and come at a cost premium over fossil-based incumbents, with biomaterial either replacing chemically identical conventional polymers—such as sugar fermented to produce ethanol and converted to ethylene for PE and PET—or creating new materials such as starch-based thermoplastics or aliphatic polyesters. Therefore, there are opportunities for innovation by chemical manufacturers and start-ups to help improve the price, performance, scale, and adoption of new and existing bio-based options.

As the demand for renewable and bio-based feedstocks grows, pressures on ecosystems will increase. Differing interests are likely to collide in the future, such as sourcing more renewable feedstocks to replace fossil fuels versus preserving biodiversity and ecosystem resilience. One question that arises from sourcing renewable feedstocks is how to manage a shift from fossil to renewable sources of carbon while protecting limited natural resources and ecosystems. Despite the positive impacts that can be derived from renewable feedstocks, they can also have potential negative externalities associated with their sourcing that must be considered and mitigated. For example, the transition to palm oil for multi-

[30] de Jong, E., Higson, A., Walsh, P., & Wellisch, M. (2012). Product developments in the bio-based chemicals arena. *Biofuels, Bioproducts and Biorefining,* 6(6), 606-624.

[31] Bomtempo, J. V., Alves, F. C., & de Almeida Oroski, F. (2017). Developing new platform chemicals: what is required for a new bio-based molecule to become a platform chemical in the bioeconomy? *Faraday Discussions,* 202, 213-225.

[32] Harmsen, P. F., Hackmann, M. M., & Bos, H. L. (2014). Green building blocks for bio-based plastics. *Biofuels, Bioproducts and Biorefining,* 8(3), 306-324.

[33] Clomburg, J. M., Crumbley, A. M., & Gonzalez, R. (2017). Industrial biomanufacturing: the future of chemical production. *Science,* 355(6320).

[34] Biotechnology Innovation Organization (BIO). Renewable Chemical Platforms Building the Biobased Economy. https://go.bio.org/rs/490-EHZ-999/images/BIO_Chemical_Companies_Report_2018_FINAL.pdf

[35] Safer Made. (2019). *Safer Materials in Food Packaging.* Retrieved from https://www.safermade.net/packaging-report

[36] Safer Made. (2018). *Safer Chemistry Innovation in the Textile and Apparel Industry.* Retrieved from https://www.safermade.net/textile-report

[37] Ellen MacArthur Foundation. (2016). *New plastics economy: rethinking the future of plastics.* Retrieved from https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics

Renewable resource impacts could be reduced by applying the regenerative principle of the circular economy to achieve more sustainable ecosystems and agriculture.

ple applications across sectors has led to significant ecosystem impacts.[38] For biological materials, issues around land and water use, competition with potential food crops, and concerns about the impacts of agricultural processes on soil (loss of topsoil), water (runoff) and air, pesticide and fertilizer use, genetic modification of crops, and loss of biodiversity have received widespread attention.[39, 40] These concerns will continue to grow as bio-based materials scale, and create questions as to the best approaches for renewable feedstock sourcing (see Box 1).

Renewable resource impacts could be reduced by applying the regenerative principle of the circular economy to achieve more sustainable ecosystems and agriculture. For example, the Environmental Paper Network identifies responsible fiber sourcing that does not lead to the loss of necessary food crops or high conservation value ecosystems such as forest and peatlands.[41] The Sustainable Biomaterials Collaborative has developed guidance on feedstock production for sustainable bioplastics that are aligned with regenerative systems. These include 1) conserve, protect and build soil, 2) conserve nutrient cycles, 3) protect air and water access and quality, and 4) promote biological diversity, among others.[39] Regenerative Organic Certified, established in 2017, is a certification for food, fiber, and personal care ingredients which includes standards for soil health, animal welfare, and social fairness. Beyond calling for the development of renewably sourced feedstocks, green chemistry could also potentially play a role in improving the safety and efficiency of agricultural practices, requiring less fertilizers, fuels and pesticides. One question in need of consideration for feedstock diversity is how to ensure new feedstocks yield materials that can also be circulated.

38 Tullis, P. (2019). *How the world got hooked on palm oil.* Retrieved from https://www.theguardian.com/news/2019/feb/19/palm-oil-ingredient-biscuits-shampoo-environmental

39 The Sustainable Biomaterials Collaborative. (2009). The Guidelines for Sustainable Bioplastics. Retrieved from https://sustainablebiomaterials.org/sustainability-criteria-tools/sustainability-criteria-tools-sustainability-guidelines/

40 Jeffries, N. (2019, March 4). Regenerative agriculture: how it works on the ground. Circulate. Ellen MacArthur Foundation. https://medium.com/circulatenews/regenerative-agriculture-how-to-grow-food-for-a-healthy-planet-9a5f637c0f3e

41 Environmental Paper Network (2018). The State of the Global Paper Industry. Retrieved from https://environmentalpaper.org/stateoftheindustry2018/

Box 1: Efficient, Large-Scale, and Consistent Versus Diverse and Dispersed: Which is Ideal in Sourcing Renewable Raw Materials?

Efficient, Large-Scale, and Consistent Versus Diverse and Dispersed: Which is Ideal in Sourcing Renewable Raw Materials?

In order to move away from fossil carbon dependence, renewable feedstocks will need to be adopted at a large scale. The question is whether scale can be achieved through multiple smaller manufacturing operations or will larger production routes that achieve economies of scale be necessary, as is the case with current fossil-based feedstocks. Some questions exist as to the consistency of renewable bio-based feedstocks (needed for chemicals and materials) that cannot be adequately achieved through diverse, smaller scale feedstocks. The companies best positioned to achieve large scale production are likely large ones with the resources necessary to research, develop, and build infrastructure for new feedstocks. Therefore, many of the successful bio-based feedstocks that will likely be adopted are those that leverage previous capital investments and are compatible with existing infrastructure and production techniques, coming from raw materials that are easily obtained in large quantities providing consistent quality.

However, agriculture is increasingly vulnerable to frequent extreme weather events as a result of climate change. Developing diverse renewable feedstocks will help shield against volatility and reduce the risk of negative supply shocks in the event of crop failures. This will be particularly important as dependency on biomaterials grows. The diversity of biological processes allows for flexibility in process technology development and the efficient scaling down of capital infrastructure expenditures, enabling nimble production.[33] For biomass crops, genetic diversity helps support ecosystem health and enhances a plant's ability to protect against stressors such as radiation, salinity, floods, drought, extremes in temperature, heavy metals, and attacks by various pathogens such as fungi, bacteria, oomycetes, nematodes and herbivores.[42, 43] Biomass can be sourced from a variety of forest products, bio-based wastes, energy crops, aquatic plants, food crops, and sugar crops but present a challenge around consistency given source variability.[21]

These issues illustrate that the renewable materials pathway to the circular economy isn't straightforward. New technologies, such as those of synthetic biology, may help address some of the limitations of current bio-based chemistry, making conversions efficient and consistent and scalable.[44] However, solutions will not likely be universal, but will require a myriad of approaches, including new renewable feedstocks and feedstocks recycled from existing petroleum-based feedstocks.

42 Somerville, C., Youngs, H., Taylor, C., Davis, S. C., & Long, S. P. (2010). Feedstocks for lignocellulosic biofuels. *Science,* 329(5993), 790-792.

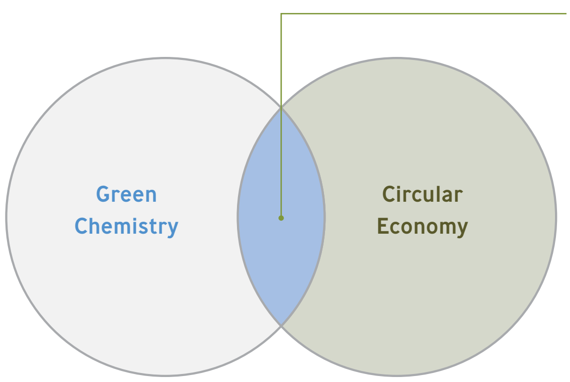
43 Gull, A., Lone, A. A., & Wani, N. U. I. (2019). Biotic and Abiotic Stresses in Plants. In *Abiotic and Biotic Stress in Plants.* IntechOpen.

44 Erickson, B., Nelson, J., Winters, P. (2012) Perspective on opportunities in industrial biotechnology in renewable chemicals. *Biotechnology Journal.* Feb; 7(2): 176–185.

Circular Economy Loop	Share
Green Chemistry Opportunities	Safety

Intersection   Key Questions

2. **GREEN CHEMISTRY OPPORTUNITIES IN SAFETY.** Eliminating known chemical hazards that would otherwise be amplified with intensified material utilization



The Intersection of Green Chemistry and Circular Economy: Safety

- The development of safer new chemicals
- The development of safer new materials or products
- The potential minimization for accidents through safer feedstocks
- Release of safer, degradable chemicals from intentional release formulated products.
- The prevention of hazardous waste generation through continued use of safe materials

Key Questions

Current State of the Market

- Do less toxic and technically viable green chemistry options exist at scale for particular chemical function/application needs?

Establishing Your Baseline

- Does your company have a chemicals management policy and staff dedicated to implementing it?
- Does your company know all of the chemicals in the formulations or materials that it sells or selects for use or in the products that it makes?
- Does your company assess the hazard profiles of chemicals it uses or supplies?
- Does your company disclose information on the chemical ingredients it uses or supplies 1) internally to other departments or business units within your organization, 2) across the supply chain to your partners, or 3) publicly to consumers?
- Does your company have a product stewardship program that addresses responsibility for chemicals offered or used cradle-to-cradle?
- Does your company work collaboratively with customers, governments, and NGOs to address consumer-based drivers for safer chemical ingredients?

Opportunities for Growth

- Does your company work to continually improve the safety profiles of the chemicals it uses or supplies?
- Can chemicals be screened for hazards further up in your supply chain?
- Does your company have voluntary safety standards for specific chemicals or chemical classes?
- Does your company work to increase the amount of chemical ingredient information it is able to obtain and disclose throughout the supply chain?
- Could your company take actions to send demand signals to help address barriers around the price, performance, or scale of adopting safer alternative chemicals?
- Could your company collaborate with others to increase your leverage to help address such barriers?

A safe and sustainable circular economy should ultimately be built on chemistries that are benign throughout their lifecycles.

Opportunities for Innovation

- Does your company have a green chemistry research program to identify priorities for substitution and/or innovation in safer and more sustainable options?
- Is your company actively working with supply chain partners or industry groups to develop or offer alternatives to substances of concern, including potential product redesign?
- Is your company actively working with supply chain partners to develop or offer safer new materials that facilitate continued use?

Considerations: Historically, the potential harm a chemical of concern will cause is calculated as risk, or a function of the degree of hazard and the amount of expected exposure. With increased materials utilization (intensified use within a set period of time), risk can increase with intensified potential for exposure. Rethinking the design of chemicals, materials, and products is a principle of both green chemistry and the circular economy. The design stage creates an opportunity and a need for collaboration across the supply chain to drive the development and adoption of green chemistry innovations.

A safe and sustainable circular economy should ultimately be built on chemistries that are benign throughout their life cycles. Choosing the safest, most sustainable building blocks for materials and products is critical, and decision-making should consider the chemicals present in the material, as well as the chemicals used to process the material, and potential byproducts created during manufacture, use, and disposal. This is necessary to achieve safer, high-performing options for specific chemical functions and applications, as well as sustainable building blocks for "circular" materials (i.e. those that are primed for circularity). Reduced toxicity is also essential in designing innovations to address any of the technology needs for circularity. Tools are needed to evaluate potential toxicity (and other trade-offs) of green chemistry solutions across the product life cycle including cumulative impacts of exposure to chemical mixtures.

Green chemistry solutions will not always be available for particular chemical functions or materials. In this case, alternative strategies will be needed to address recovering or minimizing the leakage of potentially problematic chemicals (see Box 2 on Consumable Products, below), especially in recycled materials and products (see Recycle, below). Chemical information sharing across the supply chain, and the tools necessary to facilitate it, will need to be adopted to better identify chemical innovation needs for safer solutions (see Materials Transparency in the section on Additional Pre-Conditions To Enable Green Chemistry In A Circular Economy). Further, as green chemistry solutions replace chemicals and materials of concern, a question arises of how to retire or recycle remaining stocks of or products containing those substances in an environmentally benign manner.

Box 2: Envisioning a Sustainable Pathway for Consumable Products

Envisioning a Sustainable Pathway for Consumable Products

For durable products, it is preferable to keep materials in use for as long as possible, achieved by constructing long-lasting designs and implementing practices such as reuse, repair, refurbishment and recycling to get more use out of the initial raw material extraction. For biologically-based materials, the circular economy calls for preserving or enhancing renewable resources (i.e. regeneration). One question many GC3 members face is how home and personal care products—such as laundry detergents, cosmetics, and shampoo—can achieve greater circularity given that they ultimately wash down the drain or are released into air or water.

Monitoring of surface waters has demonstrated the presence of chemicals used in common household products.[45, 46] Given this, in recent years brands have experienced increased pressure to address some of the chemical content in products that wash down the drain or are otherwise released into water supplies.

While designing products that enhance the environment is an ideal for the circular economy principle of regeneration, for consumable products best practices may be to design products that preserve or, at a minimum do not impact the environment. A challenge in designing consumable products that enhance the environment is the great uncertainty and potential unintended consequences associated with introducing foreign materials into ecological systems. Current conditions of use and the ability of existing wastewater treatment systems to break down substances may be known, but the cumulative effects of exposure to multiple low level inputs from wastewater treatment are difficult to predict. Additionally, these products do not always end up in the expected environment, for instance if a person releases them into fresh water instead of disposing of the product in wastewater which is then treated. As an example, green chemistry researchers note that given that surfactants in household cleaning products, which are often aquatically toxic, enter wastewater immediately after use, the only option for recirculation is biodegradation.[23, 47] Principle 10 of green chemistry calls for chemical products that are designed so that at the end of their function they break down rapidly into innocuous degradation products and do not persist in the environment to minimize the risk of exposure, ultimately preserving natural systems. Such degradation into benign breakdown products can enhance the circularity benefits of consumable products, particularly when New Pathways are used for their feedstock manufacture as well as reduce the impacts of unintentional leakage from other products. For other products that are not designed to be released into the environment but will likely be released—or have chemical constituents likely to be released—during their use, such as pharmaceuticals or material coatings, rapid degradation into non-toxic and non-persistent breakdown products can minimize their impact on the environment.

45 Montes-Grajales, D., Fennix-Agudelo, M., & Miranda-Castro, W. (2017). Occurrence of personal care products as emerging chemicals of concern in water resources: A review. *Science of the Total Environment,* 595, 601-614.

46 Ebele, A. J., Abdallah, M. A. E., & Harrad, S. (2017). Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment. *Emerging Contaminants,* 3(1), 1-16.

47 Brown, D. (1995). Introduction to surfactant biodegradation. In *Biodegradability of Surfactants* (pp. 1-27). Springer, Dordrecht.

Box 2 *(continued)*:
Envisioning a Sustainable Pathway for Consumable Products

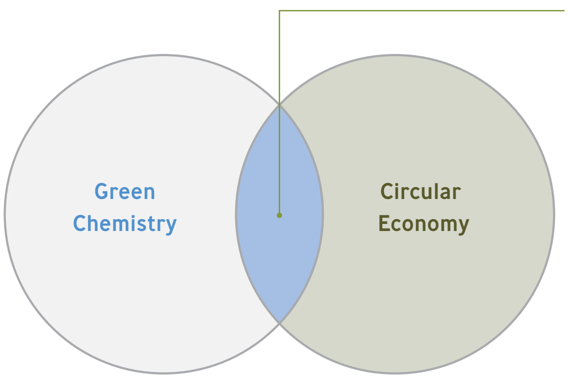
Envisioning a Sustainable Pathway for Consumable Products *(continued)*

Safe and sustainable chemicals may also improve the ability for renewable materials to be degradable. Chemicals of concern can be present with biodegradable materials that can prevent their safe degradation. For example, in fiber-based food packaging, PFAS are often used as a coating to resist moisture and oil, thus protecting both the contents and the packaging. PFAS are persistent, and therefore remain in the environment when the paper degrades.

Degradation occurs in many ways, including from exposure to light (photodegradation), oxygen (oxidation), water (hydrolysis) or from naturally occurring microorganisms, such as bacteria, fungi, and algae (biodegradation). However, designing the contents of consumable products to degrade in a benign way, leaving behind substances that do not cause toxicity or persist in the environment, is often challenging and complex.[23] The Ellen MacArthur Foundation notes that innovation to address the circularity of consumable products may lead to opportunities that are currently unknown to the economy and specifically that future technologies that may allow for the recovery of detergents after consumption.[48] Until a vision for the recovery of consumable products is achievable—both in terms of technological viability and scalability—benign degradation is a specific opportunity for safety and sustainability in need of further development.

[48] Ellen MacArthur Foundation. (2013). *Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition, Vol 1*. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

3. GREEN CHEMISTRY OPPORTUNITIES IN DURABILITY. Ensuring materials and components retain their properties and are not fatigued over prolonged and multiple use cycles



The Intersection of Green Chemistry and Circular Economy: Durability

- The development of safe new materials that can withstand prolonged use or prove beneficial in repeated applications
- The development of safe additives that can prolong the lifetime of materials, enhancing the ability for further use
- The prevention of waste through continued use of materials and their chemical content, instead of disposal
- The efficient use of energy in maximizing the utilization of material over time, reducing the need for addition resources to create virgin material

Key Questions

Current State of the Market

- Are there safe and sustainable functional chemicals available in the marketplace that can enhance the use time of materials and products?

Establishing Your Baseline

- Does your company consider the average use time for the application of the chemical or material it supplies or uses?
- Do the chemicals and materials your company uses or supplies last for the duration of the lifecycle for the product application?

Opportunities for Growth

- If end consumer products are expected to become obsolescent due to failure or fatigue, can safe chemicals be added to enhance the longevity of the use phase?
- Has your company evaluated the safety implications of the chemicals your company offers or uses to enhance the longevity of the product it makes for your customers (see the Safety section)?
- If your company uses or supplies chemicals meant to increase the durability of products beyond the expected product use time 1) does its presence enhance or inhibit further reuse, repair, refurbishment, remanufacturing, or recycling of the product or components to which it is added; and 2) are there current applications beyond the original product use cycle where this durability feature is beneficial?
- Is it economically feasible to process materials or products that contain durability enhancing chemicals for further use?

Opportunities for Innovation

- If end consumer products are expected to become obsolescent due to failure or fatigue, is your company collaborating with supply chain partners to support the development of novel chemistries to enhance the longevity of the use phase?

The overarching consideration is how to determine the appropriate durability for a product and how to strike the balance between longevity of materials and any potential toxicity concerns over time.

Considerations: One approach to reducing the need to mine or harvest new raw materials is to design them to be more durable. Durable products do not need to be replaced quickly, thus saving scarce resources. However, some chemical technologies or materials designed to strengthen, prolong, and preserve products can have undesirable characteristics. For example, given the long lifespan required for LEGO bricks, the company currently faces the challenge of finding renewable or recycled alternatives that are safe and meet the durability performance characteristics of acrylonitrile butadiene styrene (ABS) polymer, a goal LEGO aims to achieve for their brick material by 2030.[49] Per- and polyfluoroalkyl substances (PFAS) are persistent chemicals that have long been used to provide stain management and oil repellence to products, and are added to carpets, upholstery and clothing to prolong their life. However, PFAS are now increasingly restricted due to health and environmental concerns. So, while the durability benefit is clear, PFAS contamination can undercut the circularity benefit. Chemistry innovations are needed to increase the lifespan of products and enable them to be repaired, refurbished, remanufactured, and recycled. Innovations are needed to safely provide the durability function to replace these chemicals. The overarching consideration is how to determine the appropriate durability for a product and how to strike the balance between longevity of materials and any potential toxicity concerns over time.

Several companies have developed technologies to replace products with a short lifespan or enhance the useful life of products. Paints and coatings protect substrates from abrasion, oxidation, corrosion and other damage, increasing the lifetime of the underlying components. For instance, ePaint Company created an antifouling paint, ECOMINDER®, to keep boat bottoms clean of slime, algae, and bacteria, without the heavy metal content identified as problematic in traditional antifouling paint.[50] Apparel company Sheertex (formerly Sheerly Genius) partnered with their fiber manufacturer to create a new yarn made out of ultra-high molecular weight polyethylene (UHMWPE) for hosiery meant to last a decade, replacing traditional pantyhose material that tears easily.[36, 51, 52] As with all potential replacements for existing products, opportunities to reduce the hazard profile of these innovations should be considered to ensure that a replacement is not a regrettable substitute.[53] For instance, UHMWPE fibers are traditionally made with the use of two solvents (typically chemicals such as n-hexane, decalin, dodecane, kerosene, p-xylene, hexane, trichlorotrifluoroethane [TCTFE], and xylene), although safer alternatives, such as terpene can be used as viable substitutes.[54]

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49 https://www.lego.com/en-us/aboutus/sustainable-materials/

50 ePaint. (n.d.). Paint Launches Bio-based Solution to Bio-fouling Problem. Retrieved from https://www.epaint.com/2017/03/22/paint-launches-bio-based-solution-to-bio-fouling-problem/

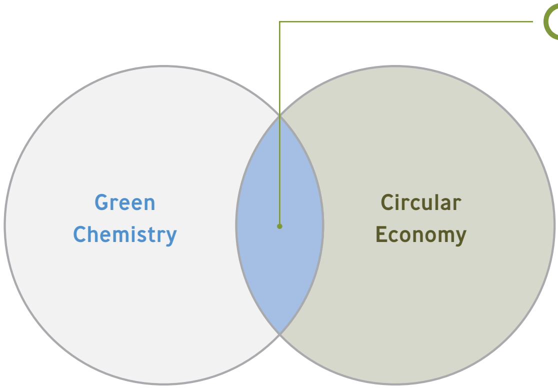
51 Sheertex. (n.d.). Sheertex. www.sheerlygenius.com

52 Findling, D. (2018, March 18) Sheerly Genius is applying technology to make hosiery durable. CNBC LLC. Retrieved from https://www.cnbc.com/2018/03/18/sheerly-genius-is-applying-technology-to-make-hosiery-durable.html

53 A regrettable substitute is a replacement for a chemical of concern that has similar or greater health or environmental impacts or lower performance.

54 Rajput, A. W., & Arain, F. A. (2014). An environmentally friendly process for the preparation of UHMWPE as-spun fibres. *International Journal of Polymer Science,* 2014.

4. GREEN CHEMISTRY OPPORTUNITIES IN INTEGRITY. Keeping chemicals in their designated places and functionalities without migrating over time



The Intersection of Green Chemistry and Circular Economy: Integrity

- The development of new chemicals and materials from which chemicals do not migrate
- The development of safer new chemicals that do not persist or cause harm if they migrate
- The development of safer chemical synthesis methods that reduce the potential for residual hazardous substances in materials
- The development of synthesis methods using innocuous auxiliary substances that reduce the potential of residual hazardous substances in materials
- The prevention of waste/emissions created by leakage from chemicals that migrate out of materials or products into the spaces people occupy, or the environment
- The efficient use of energy in maximizing the utilization of material over time, reducing the need for addition resources to create virgin material

Key Questions

Current State of the Market

- Are there safe and sustainable materials or processing of product chemistries available that would minimize potential for residual hazardous substances and/or migration from the final material or product?

Establishing Your Baseline

- Has your company assessed the safety profiles of the chemicals it uses or offers (see Safety section)?
- Of the materials your company uses, are there any substances known to migrate out of them during their production, use, or disposal (see examples for various materials in the Considerations for Integrity below)?
- Has your company assessed the potential for chemicals that it uses or supplies for packaging to migrate into products?
- Has your company assessed the potential for chemicals it uses or supplies for products or packaging to migrate into different environmental compartments, such as air, water, or soil?
- In addition to modeling and simulation of starting substances, has your company conducted direct measurements to identify non-intentionally added substances in finished materials and articles that could potentially be present and migrate out of packaging or products?
- If substances have the potential to migrate, are they designed to degrade in a way that is benign and avoids persistence and toxic intermediates (see Degradability section)?

Opportunities for Growth

- Are there options to improve the safety profile of the chemicals your company uses or offers, so that if chemicals migrate, the risk of harm can be lessened (see Safety section)?

- If your company uses or sells chemicals known to migrate into the environment, can your company switch materials or processes to safer alternatives, reduce migration in material or process design, or achieve functionality without adding such chemicals to materials?
- If your company uses or sells chemicals known to migrate out of materials, are there processes available to extract such chemicals to prevent them from passing on into future applications (see Purity section)?

Currently, there are opportunities across every material cycle to develop new chemicals, materials and processes to address chemicals of concern that have the potential to migrate.

Opportunities for Innovation

- If your company uses or sells chemicals known to migrate, can your company work with the supply chain to develop replacement chemicals or materials that are safer?
- If your company uses or sells chemicals known to migrate, can your company work with the supply chain to develop replacement chemicals or materials with lower potential exposure?
- If your company uses or sells chemicals known to migrate, can your company work with the supply chain to redesign products so that such additive chemicals are no longer needed?

Considerations: One particular concern around safety is the possibility for potentially toxic substances to migrate or leach out of materials, into unintended parts of products or into people's homes, workplaces, or the environment. A specific application where migration can be particularly troublesome is food packaging.[55] Substances emitted into air and water from such packaging can expose people to hazardous chemicals (see, for instance, PFAS coatings on fiber products[35]). Another example of migration has occurred with polybrominated diphenyl ethers (PBDEs), flame retardants previously used in products such as foam cushions, carpets, and electronics, and detected in household dust[56, 57] as well as discovered in the Arctic due to their ability to migrate far distances.[58, 59] Green chemistry solutions that minimize toxicity and migration are needed, particularly where the functionality of these chemicals is needed and if materials and products are intended to last longer or be utilized in future use cycles. Ideally, reducing chemical complexity of materials can reduce the amount of added chemistry that can migrate or react to form byproducts that can then migrate.

Currently, there are opportunities across every material cycle to develop new chemicals, materials, and processes to address chemicals of concern that have the potential to migrate. Particular additives and byproducts present in plastics, such as plasticizers, antioxidants, monomers and oligomers, light stabilizers, and slip additives have the potential to migrate.[60] For pulp and paper, chemicals of concern

55 Geueke, B., Groh, K., & Muncke, J. (2018). Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials. Journal of Cleaner Production, 193, 491-505.

56 Wu, N., Herrmann, T., Paepke, O., Tickner, J., Hale, R., Harvey, E., Webster, T. F. (2007). Human exposure to PBDEs: associations of PBDE body burdens with food consumption and house dust concentrations. *Environmental Science & Technology,* 41(5), 1584-1589.

57 Dodson, R. E., Perovich, L. J., Covaci, A., Van den Eede, N., Ionas, A. C., Dirtu, A. C.,… & Rudel, R. A. (2012). After the PBDE phase-out: a broad suite of flame retardants in repeat house dust samples from California. *Environmental Science & Technology,* 46(24), 13056-13066.

58 De Wit, C. A., Alaee, M., & Muir, D. C. (2006). Levels and trends of brominated flame retardants in the Arctic. *Chemosphere,* 64(2), 209-233.

59 De Wit, C. A., Herzke, D., & Vorkamp, K. (2010). Brominated flame retardants in the Arctic environment—trends and new candidates. *Science of the Total Environment,* 408(15), 2885-2918.

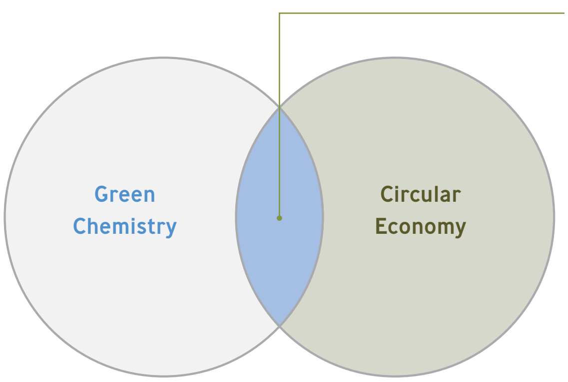
60 Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., & Purnell, P. (2018). An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. *Journal of Hazardous Materials,* 344, 179-199.

could be present and possibly migrate, originating from fillers, retention aids, sizing agents, coatings, biocides, synthetic binders, printing inks, adhesives, photo initiators, solvents, plasticizers, surfactants, and pigments.[55] Specifically, chemicals such as bisphenols, phthalates, mineral oil hydrocarbons, diisopropyl naphthalenes, heavy metals, and 2-phenylphenol that have the potential to migrate out of the material have been found in paper.[55] In some instances, metal can coatings meant to prevent reactions between packaging and the products they protect may leach and not fully prevent metal migration[61] and steel may contain metal impurities, alloying elements, and other contaminants.[62] Recycled glass may have trace elements of lead, chromium VI, and cadmium—either naturally occurring as trace elements or as a result of previous applications such as fluorescent light bulbs and television screens—that may migrate into food.[55]

CIRCULAR ECONOMY LOOP	REFURBISH/REMANUFACTURE
GREEN CHEMISTRY OPPORTUNITIES	REVERSIBILITY • REPAIRABILITY

Intersection   Key Questions

5. GREEN CHEMISTRY OPPORTUNITIES IN REVERSIBILITY. Enabling parts and components to come apart without excessive use of physical or chemical force, while maintaining performance



The Intersection of Green Chemistry and Circular Economy: Reversibility

- The development of safe new materials that can be joined for parts and components yet easily come apart for continued use and reuse, instead of being discarded
- The development of safe new adhesives and joining methods made out of renewable components that can enable parts and components to come apart easily
- The prevention of waste through continued use of materials and their chemical content, instead of disposal
- The efficient use of energy in developing adhesives that require low heat input to create the bond and little force to release it, as well as by maximizing the utilization of joined material over time, reducing the need for additional resources to create virgin material

61 Grob, K., Biedermann, M., Scherbaum, E., Roth, M., & Rieger, K. (2006). Food contamination with organic materials in perspective: packaging materials as the largest and least controlled source? A view focusing on the European situation. *Critical Reviews in Food Science and Nutrition,* 46(7), 529-535.

62 Cederberg, D.L., Christiansen, m., Ekroth, S., Engman, J., Fabech, B., Gujonsdottir, K., Håland, J.T., Jonsdottir, I., Kostaomo, P., Legind, C., Mikkelsen, B., _Olafsson, G., Svensson, K., 2015. Food contact materials—metals and alloys. (2015). *Nordic Guidance for Authorities, Industry and Trade.* http://norden.diva-portal.org/smash/get/diva2:816816/FULLTEXT02.pdf.

Key Questions

Current State of the Market

- Are safe and sustainable switchable adhesives (reverts from bonding surfaces to not on-demand without excessive use of physical or chemical force) available to meet the joining needs for different types of products?
- Are safe adhesives available to meet the joining needs of different types of products that will not contaminate the recycling stream of the material they are bonded to (e.g. nylon from carpet, paper from repositionable notes)?

Establishing Your Baseline

- Has your company assessed the safety profile of the adhesives that it supplies or buys (see Safety section)?
- For adhesives your company supplies or buys, can the bond be reversed without the excessive use of physical or chemical force?
- For adhesives your company supplies or buys, can the adhesive easily be removed to enable material recycling?
- Has your company prioritized the ease of access of components so that those with either the highest value or risk are most accessible for end of life processing?

Opportunities for Growth

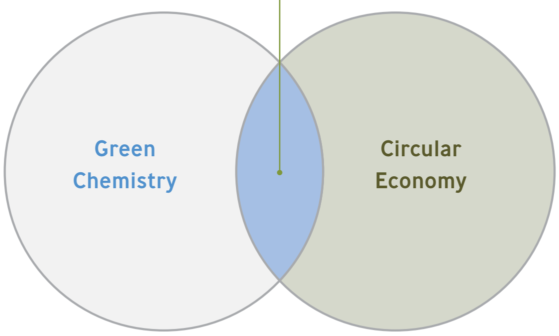
- Could your company reduce the number of different materials in end products, so less disassembly of compatible materials is required, and inseparable materials are compatible to prevent contamination of streams that cannot be isolated from one another (see Separability section)?
- Could your company simplify disassembly, making separation easy for various potential end-of-life process? This includes considerations of efficiency by employing standardized joining methods, intuitive disassembly processes, easy to understand visual cues without labels (e.g. colors, symbols, notches, etches, or mouldings), and reversal of joints without specialized tools?
- Given the time and effort required to disassemble, could your company use a more preferable method of joining (listed from most to least preferable): snapfits, other fasteners, or adhesives?
- Could your company utilize a more sustainable adhesive, potentially made out of safe renewable materials, that requires low heat input to create the bond and little force to release it?
- Could your company take actions to send demand signals to help address barriers around the price, performance, or scale of preferable adhesives?
- Could your company collaborate with others to increase its leverage to help address such barriers?

Opportunities for Innovation

- Could your company work with the supply chain to develop preferable safer adhesives?
- Could materials or products be designed to prevent the need for joining materials, mitigating the need to take components and parts apart?
- Could materials or products and their method of joining be designed from a single material to prevent the need for separating parts and components?

Considerations: The ability to disassemble products is needed to repair and replace obsolete or broken components so as to prolong the life of the product. However, design for disassembly may not take into account the need for bonding with adhesives, soldering, brazing, or welding, all of which make the component separation process more difficult and may contain chemicals of concern. Opportunities for green chemistry innovations exist in instances where mechanical attachment is not possible or preferable, such as alternatives in creating thermal or electrical contact or a gas or liquid seal. Examples of green chemistry needs for separation and disassembly, where chemicals of concern currently exist, include bonding agents, adhesives, and solders. With regards to adhesives, there is a need for green chemistry solutions that can reduce the use of substances of concern, such as chloroprene, methyl ethyl ketone (MEK), and formaldehyde. DSM-Niaga, a carpet manufacturer, applied a reversible adhesive, made from polyester—one of only two materials in the product—that releases its bond when exposed to a certain radiation frequency.[63] In the apparel industry, The Renewal Workshop takes discarded items and turns them into renewed clothing, material for upcycling, or feedstock for recycling, using liquid CO_2 to clean apparel without water, heat or harmful chemicals.[64]

6. **GREEN CHEMISTRY OPPORTUNITIES IN REPAIRABILITY.** Building up worn or fatigued materials in an additive way without having to discard large volumes



The Intersection of Green Chemistry and Circular Economy: Repairability

- The development of safe new materials that can be repaired for continued use instead of discarded
- The development of safe chemicals that can repair existing materials
- The prevention of waste through continued use of materials and their chemical content, instead of disposal
- The efficient use of energy in maximizing the utilization of material over time, reducing the need for additional resources to create virgin material

Key Questions

Current State of the Market

- Do safe and sustainable repairable materials exist for specific product functions?
- If end consumer products are expected to become obsolescent due to failure or fatigue, are there chemistries that can be added to repair materials for further use?
- Is it economically feasible to repair materials or products compared to creating new ones?

[63] Hoex, L. (2018, January 12). This reversible glue puts a screw in manufacturing. *GreenBiz.* https://www.greenbiz.com/article/reversible-glue-puts-screw-manufacturing.

[64] https://renewalworkshop.com/pages/faq

Establishing Your Baseline

- Do the chemicals and materials your company uses or supplies last for the duration of the life cycle for the product application (see Durability section)?
- Are there existing methods for the repair of the materials your company uses or supplies?
- Does your company have reverse logistics systems to collect chemicals, material, and products for repair?
- Does your company support partner organizations to collect and repair the chemicals or materials it uses or sells?
- Does your company educate consumers regarding the repairability options for your products and their chemical ingredients?

Opportunities for Growth

- Could your company adopt more materials that are repairable?
- Could your company take actions to send demand signals to help address barriers around the price, performance, or scale of safe and sustainable repairable materials?
- Could your company collaborate with others to increase your leverage to help address such barriers?
- Could your company further support partner organizations to collect and repair the chemicals or materials it uses or sells?
- Could your company further support non-technical efforts, such as policies, to help grow demand for the infrastructure for collection and repair of the chemicals or materials it uses or sells?
- Can your company increase its efforts to educate consumers regarding the repairability options for your products and their chemical ingredients?

Opportunities for Innovation

- Could your company work with the supply chain to develop new chemical processes to repair materials?
- Could your company work with the supply chain to develop new materials that can be repaired (e.g. reversible polymers, self-healing materials, or memory materials)?
- If end consumer products are expected to become obsolescent due to failure or fatigue, could your company collaborate with supply chain partners to enable the development of novel green and sustainable chemicals to enhance the longevity of the use phase?
- Could your company design products so that materials with either the highest value or risk are most protected to reduce wear or fatigue?

Many of the needs around repairability relate to product design choices, as well as systems to support infrastructure to enable repair. However, thoughtful choices in materials may help increase the reparability of products.

Considerations: In a circular economy, products are designed and built in ways that are easy to repair and assemble, so they can be easily reversed.[65] For example, screws can be used instead of permanent adhesives to join parts. Products can be assembled without proprietary fasteners, and functional components can be integrated in a way to make replacement possible. Many of the needs around repairability relate to product design choices, as well as systems to support infrastructure to enable repair. However, thoughtful choices in materials may help increase the repairability of products. For example, the use of repairable materials such as reversible polymers, self-healing materials, or memory materials (metal alloys that can be returned to original shape) may ensure repairability in products.[66] There is a need to develop specialized processes that can repair a material made from metal or plastic, without having to discard the product. To do so also requires consideration of the durability of materials (see Durability section).

Beyond chemical innovations, education, cost and policy will play a critical role in the successful implementation of any novel repairable materials. Consumer awareness of repairability and access to information for enabling repair are essential.[65] Some companies have created information campaigns and utilize third-party businesses to relay information on repair to their customers. Patagonia, for example, encourages customers to repair products rather than throw them away. The company works with iFixit, which provides consumers with tips and other useful information on how to repair Patagonia and other products, using non-proprietary materials and processes. While such partnerships currently focus on mechanical repair and the overarching system necessary to facilitate it, consideration of these potential options during the material selection and chemical design phase (as well as green chemistry innovation needs) could help devise out potential problem chemicals, increase material life, and enhance repairability.

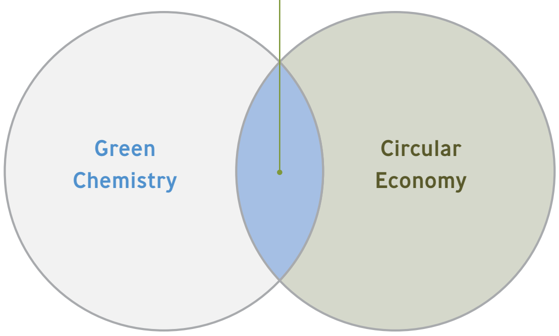
The economics of repairability is also important to consider. A product is considered economically obsolescent if the cost of ownership outweighs the cost of buying a new one.[48] In many cases, it is more expensive to repair a product than to replace it. For instance, older appliances may be more expensive for consumers to repair rather than purchasing newer, more effective models. Government incentives also exist to help replacement with more efficient product models. The Digital Right to Repair Coalition advocates for repair-friendly policies, regulations, statutes, and standards to overcome common goods restrictions to repair and reuse products.[67] To mitigate these waste streams, the Ellen MacArthur Foundation suggests emphasizing design of products that allow for disassembly and strategic replacement of parts, and allow for parts most subject to technological progress or efficiency gains to be more easily exchangeable.[48]

65 Ellen MacArthur Foundation. (2016). *Empowering Repair.* Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/ce100/Empowering-Repair-Final-Public1.pdf

66 Semsariar, M, Perrier,S. (2010) Green reversible addition-fragmentation-chin-transfer (RAFT) polymerization. *Nature Chemistry* 2; 811-812.

67 https://repair.org/association

7. **GREEN CHEMISTRY OPPORTUNITIES IN PURITY.** Removing unwanted additives and contaminants to make a pure, functional, consistent, and compatible secondary raw material, or simpler materials requiring less mixing or fewer additives



The Intersection of Green Chemistry and Circular Economy: Purity

- The development of safe new additives that do not jeopardize the recycling of materials
- The development of safe new primary and recycled materials that meet functional requirement without unwanted additives and contaminants
- The development of safe new methods to enable separation or extraction of unwanted additives and contaminants
- The prevention of waste through continued use of materials and their chemical content, instead of disposal
- The efficient use of energy in maximizing the utilization of material over time, reducing the need for addition resources to create virgin material

Key Questions

Current State of the Market

- Do new safe and sustainable materials made out of either bio-based primary or secondary raw materials exist that are pure, functional, and consistent?
- Do safe and sustainable chemistries exist to extract undesired additives and contaminants in the materials recycling process?

Establishing Your Baseline

- Does your company use or sell chemicals that enhance the performance of materials, such as finishes for metals or additives for plastics, that:
  - would require additional processing before recycling the material?
  - could contaminate the recycling stream when processed with the basic material?
  - could prevent the material from being the recycled?
- Are any of the chemical additives your company uses or sells potentially chemicals of concern (see Safety section)?
- Are there existing mechanical or chemical methods to remove the chemical additives that could inhibit recycling that your company uses or sells?

Opportunities for Growth

- Could materials be made without additives and achieve a tolerable performance?
- Could the safety profile of the material be improved with alternative additives?
- Could substitute materials that do not require additives be used?
- Could substitute materials that minimize unintended contamination be used?

Opportunities for Innovation

- Could your company work with the supply chain to develop new chemical additives that are safer or increase the ability to recycle the material?
- Could your company work with the supply chain to develop new primary or recycled materials that are safer or increase the ability to recycle the material?
- Could your company work with the supply chain to develop new materials to mitigate the need for additives?
- Could your company further support novel technologies that enable the extraction of the additives that your company uses or sells from materials where their presence inhibits recycling?

Several types of contaminants exist that can inhibit recycling and the potential to produce high quality second-life materials.

Considerations: In a circular economy, materials and products are shared, reused, refurbished and recycled. Given this extended life span, all components, materials and products require a certain purity to remain compatible with other materials of the same type to provide consistency, maintain quality and offer safety to avoid causing potential harm to humans and the environment.[48] Several types of contaminants exist that can inhibit recycling and the potential to produce high quality second-life materials. For instance, food and other debris can necessitate the extra cleaning of materials that is often financial infeasible. The quality of single resin plastics that are mechanically recycled can be compromised by the presence of small amounts of other resins. Chemical additives, such as mineral oils, phenols, phthalates, polychlorinated biphenyls and toxic metals in paper and phthalates and brominated flame retardants in plastics, in addition to other unintentional byproducts result in releases of substances that may persist and accumulate and end up in newly manufactured products.

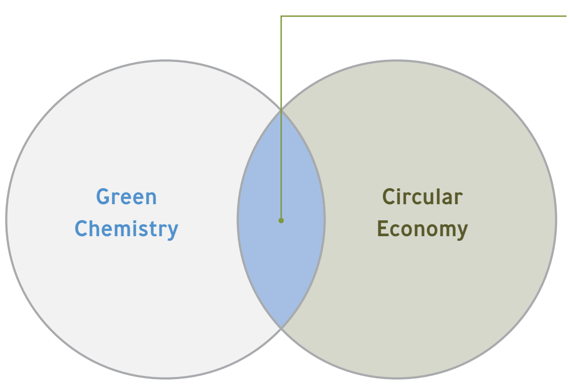
Chemical contaminants in recycled materials can be addressed in one of three ways: prevention of contamination by eliminating their use or replacing them with safe and sustainable alternatives (see Safety section), removal of contaminants, and controlling the accumulation and spread of contamination.[68] Increasing consideration of preservation of material purity (including chemical complexity) in the design of a product could increase efficiency in recapturing resources from used goods. When the functionality of materials cannot be achieved after the removal of chemicals of concern, innovations are needed to develop alternatives to those additives, including new materials that do not need additives, so that the material may be recycled. Designing safe and sustainable chemical additives and materials is preferable for achieving purity but when that is not possible, which will likely be the case for some time, innovations to remove chemicals of potential concern need to be developed to ensure safe and sustainable materials.

Separating chemicals in recycled materials starts with understanding what chemicals are present and their potential hazards. Platforms to track and understand the hazards of chemical ingredients in materials destined for recycling exist in a number

[68] Pivnenko, K. (2016). Waste Material Recycling: Assessment of Contaminants Limiting Recycling. Department of Environmental Engineering, Technical University of Denmark (DTU).

of sectors (see Transparency section). For recyclable products that are collected as a mixture of materials, separating and purifying individual chemicals or materials can be challenging, if not impossible. In many cases, the product is unrecognizable once it reaches the recycler. In some cases, materials may be recyclable, but are thrown away instead because the chemical composition is unknown (e.g., it may contain hazardous chemicals). In order to safely flow through a circular economy, post-consumer materials must be purified to a raw material or removed of potentially harmful ingredients before they can be reused in a new product. For example, historically, additives and dyes had to be chemically removed from recycled polymers, phthalates from PVC, and heavy metals from carpet backing before the base materials can be reused. Since hazardous substances are typically used in small concentrations in many materials, removing them can be costly. Safe management/disposal of these hazardous substances once removed is also a challenge.

8. **GREEN CHEMISTRY OPPORTUNITIES IN SEPARABILITY.** If composite materials are used, separating key components from each other for further use



The Intersection of Green Chemistry and Circular Economy: Separability

- The development of safe and sustainable new composite materials that can easily come apart and be separated for continued use instead of discarded
- The development of safe new methods to enable separation or extraction of high-value chemicals from composite materials
- The prevention of waste through continued use of materials and their chemical content, instead of disposal
- The efficient use of energy in maximizing the utilization of material over time, reducing the need for addition resources to create virgin material

Key Questions

Current State of the Market

- Do safe and sustainable non-composite materials exist that can fulfill the technical functions of existing composite materials?
- Can safe and sustainable new composite materials be developed that can be easily separated for recycling?

Establishing Your Baseline

- Has your company assessed the safety profiles of any composite materials it uses or offers (see Safety section)?
- Are there existing technologies to separate or extract high-value chemicals materials from blended materials?
- Are there existing technologies to separate plastics and their additives (see Purity section)?

Opportunities for Growth

- Could your company switch to use single materials in end products, so less separation of composite materials is required?
- Could the safety profile of the material be improved with alternative chemicals or materials?
- Could your company support existing technologies that enable the separation of composite materials that it uses or sells?

Opportunities for Innovation

- Could your company work with the supply chain to develop new chemical innovations to separate or extract high-value chemicals and materials from blended materials?
- Could your company work with the supply chain to develop new chemicals that could replace composite materials that have associated separation challenges?
- Could your company work with the supply chain to develop new materials that could replace composite material that have associated separation challenges?
- If your company moulds or fuses components together, can it ensure that technologies for separating chemicals exist for materials that do not come apart?

Chemical innovations to separate or extract high value materials from composite materials—such as depolymerization techniques—that do not create their own associated environmental or human health concerns are needed.

Considerations: Blended or composite materials often improve the properties of a product but can restrict their versatility for use in other future applications. While design and material selection can preclude the need to utilize such materials, end of life options must be considered in cases where their use is optimal. Chemical innovations to separate or extract high-value materials from composite materials—such as depolymerization techniques—that do not create their own associated environmental or human health concerns are needed.

Specifically, there is a need for innovation in the separation of blended and composite materials, such as multilayered plastics and their additives. For example, in the electronics industry, acrylonitrile butadiene styrene (ABS), a thermoplastic polymer, is frequently blended with additives and other plastics, such as polycarbonate, polymethyl-methacrylate, high-impact polystyrene, polybutylene terephthalate, styrene–acrylonitrile, and polyvinyl chloride, to improve both its mechanical and thermal properties.[69] For multilayer flexible film packaging, recycling is inhibited by the mixture of plastic and metal layers that provide different oxygen, moisture, gas, and UV barrier properties.[35] In the textile industry, many fabrics are a blend of two or more fibers. At the end of their useful life, these fabrics, such as cotton polyester blends, need to be separated into their respective fiber streams so that they can be successfully recycled. Innovations in mechanical separation and depolymerization technologies represent important technology options. Chemical recycling is also receiving significant attention and investment in offering a potential means to achieve this objective (see Box 3).

[69] Truc, N. T. T., & Lee, B. K. (2017). Selective separation of ABS/PC containing BFRs from ABSs mixture of WEEE by developing hydrophilicity with ZnO coating under microwave treatment. Journal of hazardous materials, 329, 84-91.

Box 3: Chemical Recycling

Chemical Recycling

What is Chemical Recycling?

Chemical recycling is increasingly being investigated and promoted as an approach to address the externalities of plastics (including waste and the limits of recycling). Chemical recycling, also termed advanced recycling, is an umbrella term that covers several end of life treatment technologies. These include:

- Purification for individual types of plastics, using solvents to extract additives and dyes, keeping the molecular structure of the plastic intact
- Depolymerization for individual types of polymers (polyester and polystyrene) into monomer or oligomer through the process of decomposition which breaks up the molecular bonds of the plastic
- Pyrolysis and gasification conversion of mixed plastics (and other materials) to liquid or gas hydrocarbon compounds, which can be cracked into petrochemicals, by thermally breaking up the molecular bonds of the plastic (note that recycling explicitly excludes processes that do not reprocess materials back into materials but instead into fuels or energy, in accordance with ISO definitions).

What are benefits and potential concerns associated with chemical recycling?

Chemical recycling should not be confused with mechanical recycling, where a plastic is melted, shredded into flakes, and processed back into polymer pellets. The benefits of chemical recycling are that waste materials that would not otherwise be recycled can be further utilized. The degree to which this is possible depends on the type of chemical recycling used. For instance, solvent-based purification can remove additives, dyes, and contaminants resulting in a polymer that can be directly converted back into a plastics product, while pyrolysis and gasification can include mixed materials that are blended, soiled, difficult to sort, or contain a substance of concern.[70] However, depending on the specific chemical recycling technique used, it potentially faces some of the same feasibility challenges as mechanical recycling, such as requirements for input quality, collection logistics, efficiency, and cost.[17] Additionally, these processes can have associated emissions, including particulates and ash-containing chemicals of concern, such as heavy metals and persistent organic pollutants—depending on the input materials, specific process technology used, and the conditions of the process, such as the temperature and whether oxygen is present. [71, 72, 73]

70 Zero Waste Europe (2019) *El Dorado of Chemical Recycling: State of play and policy challenges.* Retrieved from https://circulareconomy.europa.eu/platform/sites/default/files/2019_08_29_zwe_study_chemical_recycling.pdf

71 Kamińska-Pietrzak, N., & Smoliński, A. (2013). Selected environmental aspects of gasification and co-gasification of various types of waste. *Journal of Sustainable Mining,* 12(4), 6-13.

72 Arena, U. (2012). Process and technological aspects of municipal solid waste gasification. A review. *Waste Management,* 32(4), 625-639.

73 Rollinson, A., Oladejo, J. (2020). Chemical Recycling: Status, Sustainability, and Environmental Impacts. Global Alliance for Incinerator Alternatives. doi:10.46556/ONLS4535

Chemical Recycling (continued)

Chemical recycling presents an opportunity to capture value from materials that would otherwise be lost. However, it may be best seen as a complement to other, preferable end of life options that retain the value of a material with fewer processing inputs. Additional questions remain about the efficacy, potential to scale, and practical and economic feasibility of chemical recycling (particularly given low petrochemical feedstock prices). In addition, even if chemical recycling is fully realized, the need for systems changes that reduce materials throughput in the economy, as well as innovative green chemistry solutions, will remain. Further details about the advantages, barriers, challenges, and development opportunities for chemical recycling can be found in the European Commission's *A Circular Economy for Plastics* report.[17] Some remaining questions regarding chemical recycling include: 1) Since the output of thermochemical feedstock recycling can be a generic hydrocarbon mix, how to ensure that it is used in a circular way and not simply used as a fuel (which would be linear)?[70, 73, 74] 2) Are the economic and energy requirements of a conversion loop for chemical recycling competitive with other approaches?[70, 73, 74] If not, does it need to be subsidized?; 3) What are the potential emissions, byproducts, and wastes generated by chemical recycling and can these be safely managed?;[70, 73, 74] and 4) How much effort should be put into the research and development of chemical recycling as a solution in relation to other circular chemical and material design approaches?[73] Chemical companies are exploring some of these questions in potential renewable content crediting models[75] and pilot project facilities as they seek solutions to address the prevalence of existing materials.

Given the extent of plastics already in the economy and the need to reduce the use of new fossil inputs to make chemicals and materials, safe chemical recycling could present an important and sustainable route to new chemical production from otherwise waste material. Given the complexity surrounding chemical recycling, further research into the various associated technological options is needed to establish clear criteria for safe and sustainable chemical recycling solutions.

74 IN4climate.NRW (Ed.) 2020: Chemical Plastics Recycling—Potentials and Development Perspectives. A contribution to defossiling the chemical and plastics processing industry in NRW. A discussion paper by the Circular Economy Working Group. Gelsenkirchen.

75 Co.Project Mass Balance (2019). Enabling a Circular Economy for Chemicals with the Mass Balance Approach. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/Mass-Balance-White-Paper-2020.pdf

Making transparency commonplace across industries and supply chains, whether through sectoral standards or policies, ensures better accuracy and awareness of where problematic ingredients are being used and where innovation in green and sustainable chemistry is needed.

Additional Pre-conditions to Enable Green Chemistry in a Circular Economy

In addition to technical barriers of performance, quality, and consistency of materials reused in the circular economy, there are a number of non-technical barriers to a safe and environmentally sound circular economy. For example, many policies still favor virgin materials extraction and do not fully account for the total costs of resource degradation or waste accumulation. The logistics and infrastructure for recycling and for moving secondary materials to end markets or products to locations with workers who can refurbish them with proper safety procedures in place are not developed and the infrastructure for composting at end of life is also limited. According to research commissioned by the GC3, there are also barriers to creating green chemistry innovations. These include the time and expense to research, develop, and commercialize new green chemicals; incumbency of existing chemicals that are capitalized and integrated into complex value chains; potential performance, cost, or risk tradeoffs involved in switching from existing chemicals; a lack of alignment in the supply chain; and insufficient demand.[76] While research and development funding and financing are increasing for investments in circular materials, significant additional investment in green chemistry innovation is needed. These barriers will need to be addressed by businesses, policymakers, NGOs, and others in order to fully enable a circular economy.

Industry and research institutions play a critical role in creating innovations that address the eight categories of green chemistry opportunities outlined above. These innovations include not only chemical and material innovations but also business model innovations, such as product-service systems, refurbishing or repurposing, and leasing. Educational institutions play an essential role in creating the curriculum and interdisciplinary programs and rewards that train the next generation of engineers, chemists, health scientists, and others to create materials that are safe, sustainable, and circular.[77] Organizations such as Beyond Benign, a non-profit that develops curriculum and collaborations in green chemistry education, and the International Sustainable Chemistry Collaborative Centre, an international organization focused on advancing education and innovation in sustainable chemistry, are working to ensure a future workforce ready to meet the challenges and opportunities of both circularity and green chemistry.

The following are three specific pre-conditions needed to enable a safe and sustainable circular economy.

Materials Transparency **Sharing information on the chemical constituents of a product or material.**

To understand where potentially problematic chemicals exist that can inhibit safe and sustainable circularity, transparency of chemical ingredients in materials and products across value chains is required.[48] Making transparency commonplace throughout industries and supply chains, whether by means of sectoral standards or policies, ensures better accuracy and awareness of where problematic ingredients are being used and where innovation in green and sustainable chemistry is needed. Certain industries, such as the automotive, electronics, and building sectors have already developed systems (including standards) for sharing business-to-business chemical ingredient information, often in response to end-of-life product waste and take-back policies or market pressures. These include approaches such

[76] Tess Fennelly & Associates. (2015). *Advancing Green Chemistry: Barriers to Adoption & Ways to Accelerate Green Chemistry in Supply Chains.* Green Chemistry and Commerce Council. March 2015. Accessible at: https://greenchemistryandcommerce.org/documents/Advancing-Green-Chemistry-Report-June2015.pdf

[77] Wood PLC and Lowell Center for Sustainable Production (2019). Chemical Innovation Action Agenda: Transition to Safer Chemicals and Technologies. European Commission Report: Contract No 07.0201/2018/776820/ETU/ENV.B2

Accountability is a key consideration in an economy based on sharing or reuse. Reuse and recycling reduce waste in a circular economy, but raise the question of how accountability can be ensured for the safety of secondary materials.

as the International Material Data System (IMDS), IPC175X, and Health Product Declarations (HPDs). Many retailers are using systems created by UL and others to collect information on intentionally added ingredients in formulated products. For some product categories, such as cleaning product formulations and toys, state regulations are requiring disclosure of chemical ingredients. However, sometimes specific chemical types, such as fragrances, are considered trade secrets and are not disclosed. Many consumer goods companies, such as Beautycounter and Seventh Generation, have chosen to voluntarily disclose the full list of ingredients used in their products and will not work with suppliers who do not provide that same information to them. However, the multitude of requirements and reporting systems with different formats can create a burden for companies that must provide information if they are not aligned. Creating consistent, shareable, information formats for products, particularly solid articles, is an important need for the future.

An increasing number of companies and non-profit groups, such as the Environmental Working Group (EWG), ChemForward, ToxNot, UL, and SciVera, create and maintain databases or other systems that review the hazards of ingredients present in products in order to educate supply chains and individual consumers on hazards associated with a wide range of chemical ingredients. This allows consumers to make informed purchasing decisions. Levi Strauss & Co's Screened Chemistry Program checks chemical formulations against human and environmental health endpoints to provide a list of safer chemicals for use in the design process.[78] The company is collaborating with apparel industry groups, such as the Zero Discharge of Hazardous Chemicals initiative, to share their screening system industry-wide.

New big data approaches and digitization may provide important opportunities to improve tracking of material and product constituents in a circular economy to improve design as well as safe and sustainable recycling and reuse.

Accountability. **In a more distributed ownership and user model, ensuring that legal accountability for chemical risks is clear and transparent**

Understanding where to place accountability for the hazards of materials throughout their life cycle is challenging for both shared and ownership-based economies (where individuals own products versus using a service). In a linear model of resource consumption, the responsibilities of chemical and facility waste management, compliance and dissemination of hazard or safety information generally falls on manufacturers and retailers. However, responsibility for the fate of goods at end of life is less clear (for example when electronics or plastics are recycled or burned in third world countries), but often fall on individual consumers and governments. In some cases, take-back policies extend accountability for materials through their end of life. Through building safety into design, industries can reduce accountability issues downstream. For example, in addition to obtaining full material chemical ingredient information, many companies develop restricted substance lists (RSL's) to ensure that regulated or other priority chemicals are not present in finished products over a certain threshold.

Accountability is a key consideration in an economy based on sharing or reuse. Reuse and recycling reduce waste in a circular economy, but raise the question of how accountability can be ensured for the safety of secondary materials. For example, if a used article of clothing is repurposed by another company into a bag, who is held accountable for the eventual breakdown of the material and potential release of microplastics or other toxic materials into the environment? Similar questions can be asked for recycled products that are broken down into new materials, especially if the origin of the recycled material is unclear and systems are not in place to track chemical constituents. This problem is common for many waste streams. Consumers are becoming more open to an economy of shared access (goods change hands but ownership does not) versus ownership. For

[78] Strand, R., Mulvihill, M. (2016). Levi Strauss & Co.: driving adoption of green chemistry. Berkeley Hass Case Series. Haas School of Business, University of California Berkley. Retrieved from levistrauss.com/wp-content/uploads/2016/11/UC-Berkeley_Haas-Case-Study_Driving-Adoption-of-Green-Chemistry.pdf

Chemical leasing, which is being promoted by several governments and companies, utilizes the product-as-service business model, where chemical suppliers sell the function performed by the chemical rather than selling chemicals by volume. The supplier provides the chemicals management service and shares knowledge about safe management with the chemical user, creating shared responsibility and an incentive for both reduced material/chemical use and lower toxicity.

example, automobile sharing (Zipcar), clothing rental (Rent the Runway), and machinery rental (hardware store tool libraries) are becoming more mainstream.[48] However, accountability for risks is not well developed for a sharing economy.

A primary mechanism to ensure accountability in the circular economy is consistent government policy and compliance with those policies (in absence of such policies industry standards can provide a similar mechanism). Policies can provide strong signals of materials to avoid, establish standards for recycled or renewable content of products and extend responsibility through to end of life. Transnational companies frequently have to comply with a complex landscape of often conflicting policies, which in the absence of global harmonization, can lead to increased costs and lower standards in some regions creating a disadvantage for more sustainable materials, and potential trade-offs. Policies can also create conflicts between green chemistry and circularity goals. The European Commission's Green Deal policy framework notes the needs for integrated policies that address toxicity, circularity and climate concurrently to avoid trade-offs.[79]

One way to retain material responsibility within one entity is to create a closed loop for products. The company or retailer that distributes goods is also charged with collecting used goods for redistribution or decommission. The office furniture manufacturer, Steelcase, has developed and implemented competitive decommissioning, trade-up, and rental programs aimed at diverting furniture from landfills and promoting the flow of assets (product and materials) through reuse, resale, repair, refurbishment, and material recovery.[80] The furniture company has created a hub called ReMarket to redistribute second-hand goods and materials throughout their dealer network. This example demonstrates a company's ownership of responsibility beyond the primary use of their products. Another approach to shared accountability is chemical leasing. Chemical leasing, which is being promoted by several governments and companies, utilizes the product-as-service business model, where chemical suppliers sell the function performed by the chemical rather than selling chemicals by volume.[81] The supplier provides the chemicals management service and shares knowledge about safe management with the chemical user, creating shared responsibility and an incentive for both reduced material/chemical use and lower toxicity.[82]

Collaboration. Collaboration within sectors and across the value chain to achieve both circular economy and green chemistry goals.

Collaboration is needed across supply chains to understand chemical and material needs (performance and safety) and identify opportunities to co-optimize circularity and green chemistry goals. Collaboration can help address performance and cost barriers, develop agreement on standards for materials and products, establish sustainability criteria for materials, and provide an opportunity to share experiences and best practices. For example, GC3 research indicates that it is often not the lack of technical capacity to create new, innovative, more circular, chemicals that is the problem, but instead a lack of market demand, where customers will not pay a premium for such solutions. Brands and retailers express their need for supplies of safer, more sustainable chemical and material alternatives in creating products, but may not be willing to invest the money and time required to develop, commercialize, and receive approvals for alternatives.

79 European Commission. (2019). The European Green Deal. Retrieved from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

80 Steelcase Inc. (2020). *Promise + Progress: Impact Report 2019.* Retrieved from https://www.steelcase.com/content/uploads/2020/02/Steelcase-2019-Impact-Report.pdf

81 United Nations Industrial Development Organization (UNIDO), Materials and Chemicals Management Division, Global Chemical Leasing Programme. Chemical Leasing. https://chemicalleasing.org/

82 Ohl, C., & Moser, F. (2007). Chemical leasing business models—a contribution to the effective risk management of chemical substances. *Risk Analysis: An International Journal,* 27(4), 999-1007.

This Blueprint can be used to engage internal and supply chain stakeholders in identifying needs and opportunities along the product value chain to co-optimize green chemistry and circularity goals.

Ultimately, supply chain dialogue and collaboration can help identify barriers (such as cost) while developing strategies that share costs, risks, and benefits with all parties seeking to develop, source, and sell safer, more circular materials and products.

These technical and collaboration needs must be supplemented by a supportive policy environment that incentivizes circularity and green chemistry (including research, commercialization and adoption) and supports the creation of infrastructure to enable secondary materials utilization.

Conclusion

Green chemistry can play an essential role in optimizing circular economy systems, helping shift from the traditional 'take-make-waste' linear model, toward a regenerative approach that reduces reliance on the consumption of finite resources. Two foundational green chemistry tenets, designing safer chemicals and utilizing renewable feedstocks, can be applied constructively across the entire circular economy model. Other green chemistry principles can be utilized at different stages in the circular economy model to enhance the overall benefit of the system.

In examining the potential role of green chemistry within existing circular economy models, it is clear that tensions can exist between the required attributes to achieve circularity and the "greenness" of the underlying chemistry. For example, multiple uses of a material can reduce overall impact—but may require additive chemistries with less desirable health and environmental profiles to create technically viable materials that withstand multiple uses. It is in these situations where green chemistry and circular economy goals can be co-optimized to drive safer, more sustainable and circular materials.

This report identifies eight areas, mapped to the widely accepted Ellen MacArthur Foundation circular economy "butterfly" model, where green chemistry innovation can enhance the desired positive attributes of circularity, while minimizing potential unintended negative impacts. Loosely considered, these eight areas of opportunity focus on: renewable feedstocks; eliminating hazards; reducing chemical and material complexity; and increasing durability, separability, reuse, and recyclability of materials.

The GC3 Blueprint of Green Chemistry Opportunities for a Circular Economy provides a framework to support materials development and selection as companies and others seek to transition towards a safe and sustainable circular economy. This Blueprint can be used to engage internal and supply chain stakeholders in identifying needs and opportunities along the product value chain to co-optimize green chemistry and circularity goals. It is designed as a flexible approach that allows for a broad group of industries and other stakeholders to map and assess current research and development and sourcing activities and ultimately identify opportunities for innovation. Finally, while the overlap between the green chemistry principles and circular economy framework are not completely intuitive or clear, the Blueprint has been developed as a starting point for conversation that engages both communities in co-optimizing the goals of these complementary approaches in a concerted fashion.

Fully realizing the promise of green chemistry to optimize circularity requires more than technical innovation. There are larger systemic barriers that must be also addressed, including policy frameworks that can disadvantage efforts to achieve circularity, and gaps in logistics systems and infrastructure to fully recycle and reuse materials. Further barriers include the challenges of development, commercialization, and scaling of green chemistry solutions that replace incumbent, cost-effective chemistries. To fully realize the role green chemistry can play in enhancing circularity will require not only technical innovation, but creative collaboration among industry, government, and other stakeholders to address systemic barriers. It will necessitate policies that incentivize the development and commercialization of green chemistry, and value chain partnerships to understand key drivers, clarify functional needs, and develop creative win-win solutions.

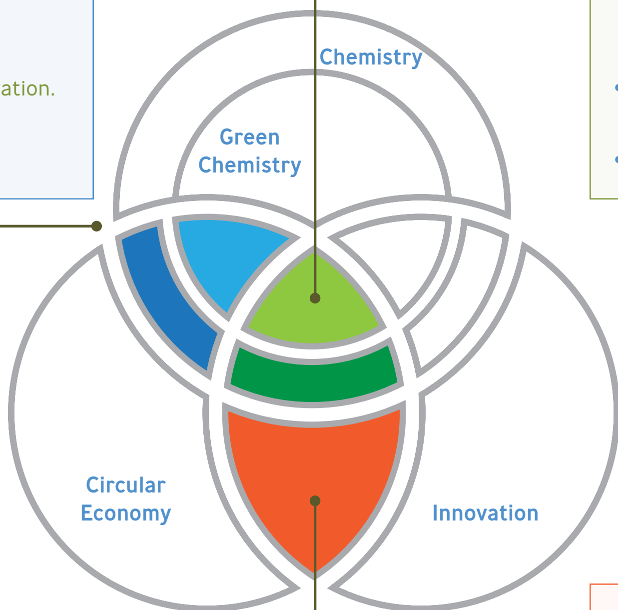
Green chemistry offers significant opportunities in the continuing evolution of the circular economy model. Collectively addressing these innovation needs—whether technical or systemic—can accelerate development of the next generation models of circularity that can achieve greater impact with safer and more sustainable chemistries.

Appendix

The Process for Identifying Green Chemistry Needs to Support a Circular Economy

Research Part A: Role of Chemistry in Enabling the Circular Economy

- Understand current intersection between Chemistry and the Circular Economy
- Identify what is lacking, and where there is need for innovation.
- Differentiate aspects that are green chemistry



GC Innovation in Support of the Circular Economy

- Expert interviews to identify universal barriers in transitioning to circular systems
- Industry interviews to understand how companies are integrating circularity considerations into their R&D, sourcing decisions and product design, as well as key chemistry challenges they face in achieving circularity goals
- Interviews with innovators to identify current solutions being developed
- Research parts A & B

Research Part B: Innovation for Circular Economy

- Understand Circular Economy innovation needs
- Determine strategies to transition to and create for circular systems
- Identify how those needs can be filled by chemistry
- Differentiate aspects that are green chemistry

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