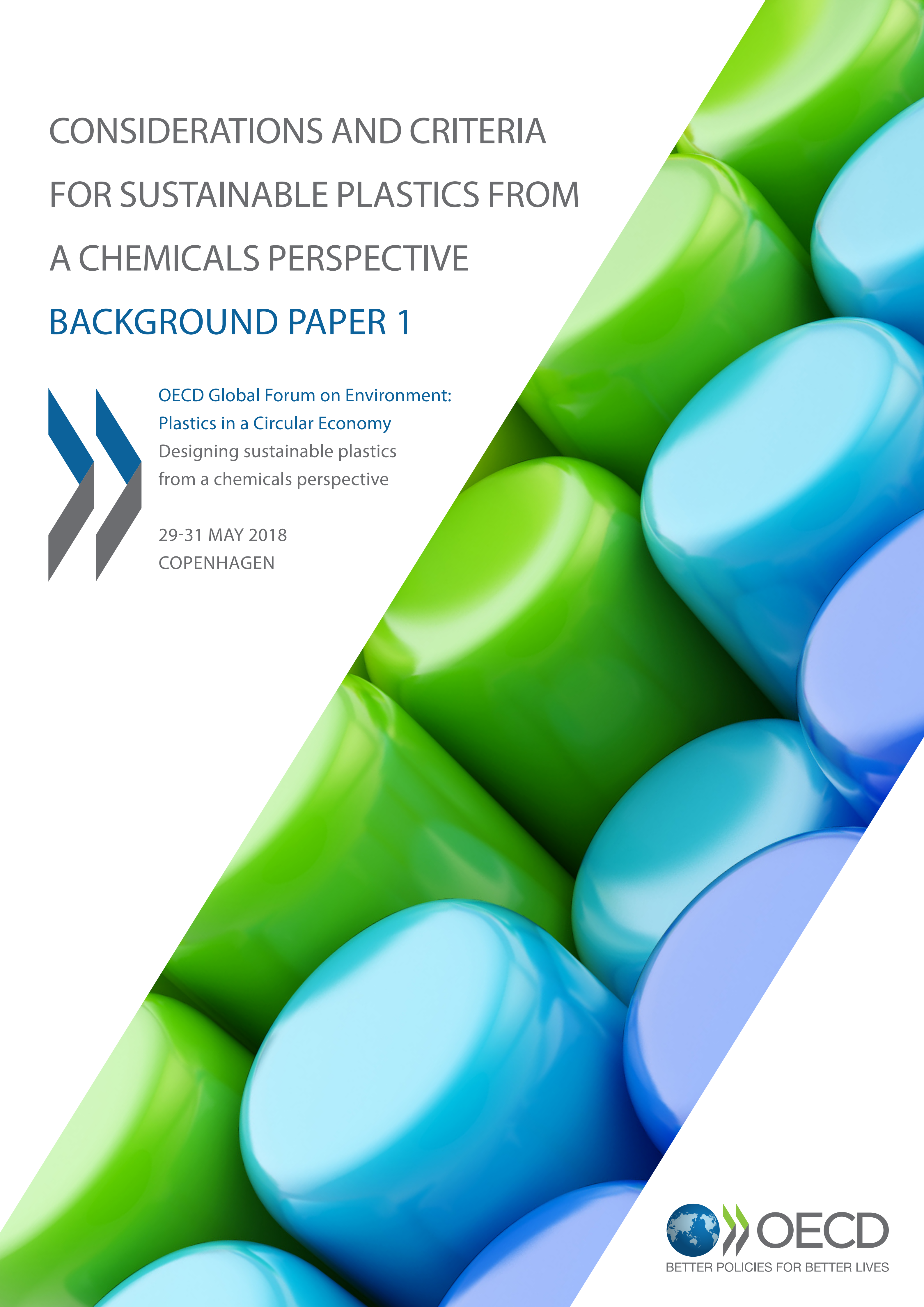
CONSIDERATIONS AND CRITERIA FOR SUSTAINABLE PLASTICS FROM A CHEMICALS PERSPECTIVE

BACKGROUND PAPER 1

OECD Global Forum on Environment:
Plastics in a Circular Economy
Designing sustainable plastics
from a chemicals perspective

29-31 MAY 2018
COPENHAGEN



OECD
BETTER POLICIES FOR BETTER LIVES

OECD Environment, Health and Safety Publications
Series on Risk Management
No. 53

Considerations and Criteria for Sustainable Plastics from a Chemicals Perspective

IOMC
INTER-ORGANIZATION PROGRAMME FOR THE SOUND MANAGEMENT OF CHEMICALS
A cooperative agreement among FAO, ILO, UNDP, UNEP, UNIDO, UNITAR, WHO, World Bank and OECD

Environment Directorate
ORGANISATION FOR ECONOMIC COOPERATION AND DEVELOPMENT
Paris 2019

About the OECD

The Organisation for Economic Co-operation and Development (OECD) is an intergovernmental organisation in which representatives of 36 industrialised countries in North and South America, Europe and the Asia and Pacific region, as well as the European Commission, meet to co-ordinate and harmonise policies, discuss issues of mutual concern, and work together to respond to international problems. Most of the OECD's work is carried out by more than 200 specialised committees and working groups composed of member country delegates. Observers from several countries with special status at the OECD, and from interested international organisations, attend many of the OECD's workshops and other meetings. Committees and working groups are served by the OECD Secretariat, located in Paris, France, which is organised into directorates and divisions.

The Environment, Health and Safety Division publishes free-of-charge documents in twelve different series: **Testing and Assessment**; **Good Laboratory Practice and Compliance Monitoring**; **Pesticides**; **Biocides**; **Risk Management**; **Harmonisation of Regulatory Oversight in Biotechnology**; **Safety of Novel Foods and Feeds; Chemical Accidents; Pollutant Release and Transfer Registers; Emission Scenario Documents; Safety of Manufactured Nanomaterials;** and **Adverse Outcome Pathways.** More information about the Environment, Health and Safety Programme and EHS publications is available on the OECD's World Wide Web site (www.oecd.org/chemicalsafety/).

This publication was developed in the IOMC context. The contents do not necessarily reflect the views or stated policies of individual IOMC Participating Organizations.

The Inter-Organisation Programme for the Sound Management of Chemicals (IOMC) was established in 1995 following recommendations made by the 1992 UN Conference on Environment and Development to strengthen co-operation and increase international co-ordination in the field of chemical safety. The Participating Organisations are FAO, ILO, UNDP, UNEP, UNIDO, UNITAR, WHO, World Bank and OECD. The purpose of the IOMC is to promote co-ordination of the policies and activities pursued by the Participating Organisations, jointly or separately, to achieve the sound management of chemicals in relation to human health and the environment.

This publication is available electronically, at no charge.

Also published in the Series on Risk Management: link

For this and many other Environment,
Health and Safety publications, consult the OECD's
World Wide Web site (www.oecd.org/chemicalsafety/)

or contact:

OECD Environment Directorate,
Environment, Health and Safety Division
2 rue André-Pascal
75775 Paris Cedex 16
France

Fax: (33-1) 44 30 61 80

E-mail: ehscont@oecd.org

FOREWORD

This report was prepared as a background document for the "Global Forum on Environment focusing on Plastics in the Circular Economy – Sustainable Design of Plastics from a Chemicals Perspective" that took place on 29-31 May 2018 in Copenhagen, Denmark.

The workshop was organised in co-operation between the OECD Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology (Joint Meeting) and Working Party on Resource Productivity and Waste (WPRPW), and was hosted by the Danish Government, with funding from the European Commission, Nordic Council of Ministers, Austria (Federal Ministry for Sustainability and Tourism), Germany (Federal Ministry of Environment, Nature Conservation and Nuclear Safety) and Belgium (Public Waste Management Agency of Flanders).

An expert group was formed from delegates nominated by the Joint Meeting and the WPRPW to inform the organising of the workshop in collaboration with the OECD secretariat and representatives within the Danish Government.

The document was drafted by Lauren Heine and Alex Stone for Northwest Green Chemistry and was revised following the feedback received at the Global Forum and from Delegates after the workshop. Eeva Leinala and Peter Börkey of the OECD Secretariat provided substantive inputs and guidance. The report is published under the responsibility of the Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology of the OECD.

Executive Summary

Sustainable plastics are plastic materials used in products that provide societal benefits while enhancing human and environmental health and safety across the entire product life cycle. To be considered sustainable, plastics must be managed within a sustainable materials management system (a Circular Economy)[1] to avoid the creation of waste, toxics and pollution. Even readily recyclable plastics derived from non-toxic constituents are not sustainable plastics if they end up as litter and pollute land and oceans. Creating sustainable plastics is challenging because it involves not only the development or selection of materials for use in high-performing products, but also the design of a material ecosystem in which products are made, used, and from which sustainable value from the plastics is recaptured after use. Sustainable plastics must be part of a holistic and principle-based approach to sustainable material flows. While it may not be possible to call a plastic sustainable outside of how it is used in a product, it is possible to establish criteria for plastics that are not sustainable. For example, non-recyclable plastics containing highly toxic chemicals to which workers, users, recyclers or the environment may be exposed should not be considered sustainable, even if they serve potentially valuable functions.

The considerations and criteria discussed in this report are based on principles of sustainable product design for which there is considerable consensus. Using principles to guide product development preserves flexibility, and helps to avoid being limited by what is currently measurable with available tools and metrics. While design principles do not translate directly into metrics, they do provide a directional compass for the criteria, tools and metrics that allow measurement. The considerations and criteria identified in this report are directly mapped to the American Chemical Society Green Chemistry Institute's Sustainable Design Principles[2], an overarching set of principles that are distilled from the Principles of Green Chemistry and Engineering:

- **Design systems holistically and use life cycle thinking.** This applies to the design of all sustainable chemicals, materials and products. Materials flow in dynamic environmental and economic systems. Waste from one product iteration becomes feedstock for another when designers 'design for circularity.'
- **Maximize resource efficiency**. Resource efficiency is not just about being efficient and doing more with less. It includes the imperative to preserve natural capital. Renewable resources should not be used faster than they can be regenerated. Resources that can be depleted should not be dissipated and lost to recovery, reuse and recycling. Waste is a sign of inefficiency in a system.
- **Eliminate and minimize hazards and pollution**. Risk is a function of hazard and exposure. Reducing the inherent hazards of chemicals can be the most effective way to reduce risk from chemicals, materials and products. Hazards may also be physical. For example, litter is a form of unmanaged waste that can cause physical entrapment and be mistaken as food by wildlife when it leaks into the environment.

The considerations and criteria in this report are essentially derived by evaluating each life cycle stage of a plastic product for each principle above. A number of useful tools already exist to measure various aspects of sustainability and to quantify how products fulfil

elements of the design principles. Such tools include chemical inventory and disclosure, chemical hazard assessment (CHA), exposure assessment (EA), waste/circularity analysis, life cycle assessment (LCA), alternatives assessment, natural capital assessment and others. Each tool evaluates only one or, at best, a couple of attributes. These attributes are inter-related. Improvement in one area may result in changes in another. It is important to be aware of potential trade-offs and to make informed decisions.

This report was prepared with a broad audience in mind, but it is primarily focused on product designers who select plastics for use in products. However, the information within is relevant to policy makers and those who procure products. Plastics in products are looked at broadly and not limited to any plastic types, product types, or geographical regions. Future work could differentiate criteria for diverse polymer types, durable versus short-lived products and different geographic regions with different regulatory requirements and materials management infrastructures. As a first pass, the considerations and criteria in this report do not address all aspects of sustainability such as engineering performance specifications, regulatory requirements, social impact assessment or consideration of cost and availability. Comparisons between plastic and non-plastic materials are also not addressed. While these elements are all critical for sustainable product design, they are outside the scope of this report. Future work could incorporate them into the framework.

Sustainable product design is an iterative, circular process of continual improvement. The recommended first step for the product designer is to 1) establish product design goals important to their organization, including sustainability goals. The product concept, the service it will provide, technical performance specifications, market requirements and cost and availability criteria are combined with sustainable product design aspirations. Designers should use life cycle thinking in their initial product design and scoping exercises and include a plan for the product at its end-of-use. Designers can then gather information on considerations and criteria related to hazards, pollution, waste/circularity and natural resource impacts for each life cycle stage, starting with 2) feedstock selection, 3) production and manufacturing (may have multiple sub-stages), 4) product use, and 5) end of use. After assessing each independent life cycle stage, the designer is encouraged to 6) take another holistic look at the product design and benchmark it against other products that provide the same desired service. The designer can then review and synthesize the information gathered for 7) evaluation and optimization against the design principles, and then make improvements as needed. A holistic and principle-based approach to product design can drive both incremental improvements and disruptive innovations.

This report was prepared to support discussions at the OECD Global Forum on Environment: Plastics in a Circular Economy – Designing Sustainable Plastics From a Chemicals Perspective, that was hosted by the Danish Government in May 2018 and co-organised by the OECD's Chemicals Committee and the Environmental Policy Committee's Working Party on Resource Productivity and Waste. Following discussions and feedback at the meeting the report was updated.

Table of contents

1. Introduction

Sustainable plastics are plastics used in products that provide societal benefits while enhancing human and environmental health and safety across the entire product life cycle. In order to be considered sustainable, plastics must be managed within a sustainable materials management system (a Circular Economy) to avoid the creation of waste, toxics and pollution. Even easily recyclable plastics derived from low hazard constituents are not sustainable plastics if they end up as persistent litter or if they are dispersed into water as microplastics.[3] Creating sustainable plastics is challenging because it involves not only the development or selection of materials for use in high-performing products, but also the design of a material ecosystem in which products are used and from which sustainable value from the plastics is recaptured after use. Sustainable plastics must be part of a holistic approach to sustainable material flows.

The considerations and criteria discussed in this report are based on principles of sustainable product design on which there is considerable consensus. Using principles to guide development preserves flexibility and helps to avoid being constrained by available criteria, tools, and metrics. While design principles do not translate directly into metrics, they do provide a directional compass for the criteria, tools and metrics that allow for measurement. The considerations and criteria identified in this report are directly mapped to the American Chemical Society Green Chemistry Institute's Sustainable Design Principles4, an overarching set of principles for sustainable product design that are themselves distilled from the Principles of Green Chemistry and Engineering:

- **Design systems holistically and use life cycle thinking.** This broad and overarching principle applies to the design of all materials, including plastics. A plastic is not inherently sustainable. Rather, its sustainability is tied to the dynamic context in which materials flow in environmental and economic systems. Waste from one product iteration becomes feedstock for another when designers 'design for circularity.'
- **Maximize resource efficiency**. Resource efficiency is not just about being efficient and doing more with less. It includes the imperative to preserve natural capital. Renewable resources should not be used faster than they can be regenerated. Non-renewable resources should not be dissipated and lost to recovery, reuse and recycling. Waste is a sign of system inefficiency.
- **Eliminate and minimize hazards and pollution**. Risk is a function of hazard and exposure. Reducing the inherent hazards of chemicals reduces risk from chemicals, materials and products. Hazards may also be physical. For example, litter is a form of unmanaged waste that causes great harm to wildlife and can end up in human and animal food supplies.

In 2010, the Organisation for Economic Co-operation and Development (OECD) established four Policy Principles for Sustainable Materials Management (SMM):[5]

1. Preserve natural capital.
2. Design and manage materials, products and processes for safety and sustainability from a life cycle perspective.

3. Use the full diversity of policy instruments to stimulate and reinforce sustainable economic, environmental and social outcomes.
4. Engage all parts of society to take active, ethically-based responsibility for achieving sustainable outcomes.

These principles capture the complexity of the challenge from product design, policy, and societal perspectives. Principle 3 drives the adoption of sustainable materials through the alignment of policy initiatives such as chemical restrictions, taxes and incentives, procurement requirements, and voluntary product stewardship. Principle 4 recognizes that all parts of society to play a role in sustainable materials management through decisions about product design, development, procurement, and waste management. Manufacturers and product developers, however, have the primary influence on the selection of polymer types and product design decisions.

Both the sustainable product design principles and the SMM Policy Principles are subsets of the United Nations (UN) Sustainable Development Goals (SDGs); particularly UN SDGs 9: Industry Innovation and Infrastructure, 14: Life Below Water and 15: Life on Land.[6,7] The relationships between the sustainable product design principles, the SMM Policy Principles and the UN SDGs confirm their alignment. More work is needed, however, to consider sustainable product design within a broader context of sustainability. Consensus on sustainable product design principles is important because it allows for agreement on criteria that support their realization. The criteria can then pave the way to existing and emerging tools and metrics that fit the purpose of the criteria.

A number of useful tools already exist to measure various aspects of sustainability including chemical inventory and disclosure, chemical hazard assessment (CHA), exposure assessment, stakeholder assessment, alternatives assessment (AA), life cycle assessment (LCA), and others. More tools continue to be developed. Each of the existing tools evaluates only one, or at best, a few sustainability attributes. Tools and criteria need to be both dynamic and as simple as possible. Otherwise they will not be used, and may create additional barriers across the supply chain. Because sustainability considerations are heavily interrelated, improvement in one area often results in changes in another. It is important to be aware of potential tradeoffs and to make informed decisions. This report will show how these tools can be used together to realize a vision for sustainable plastics based on sustainable design principles.

Vision and principles should drive tool use and not the other way around. At times, arguments have focused on how to trade off results from one tool against results from another (e.g. LCA versus risk assessment) outside of an integrated sustainability context. Focusing on just one attribute, or even just one principle, can lead to unsustainable results. For example, a plastic substance, no matter how recyclable or safe the ingredients used, can still cause harm if the product ends up as litter. Likewise, chemicals derived from rapidly renewable, biobased feedstock can have benefits at the feedstock life cycle stage but can be made into highly toxic substances. Therefore, one should not focus on one facet, or single principle of sustainable product design. The principles should be optimized concurrently.

Our collective understanding of sustainable plastics will continue to evolve as innovation occurs in multiple realms. A product accepted as sustainable today may not be so in the future, and vice versa. For example, a plastic may contain chemicals, even those of low hazard, that are not compatible with new recycling technologies. Likewise, plastics that may seem unsustainable with respect to circularity may become recyclable in the future.

For example, thermosets and composite materials are currently not easily recycled but research described in Box 1 below points to future potential. A need exists for innovative plastics that both provide desirable performance properties and can be managed for circularity after use. Box 1 describes some examples of current areas of innovation.[8,9]

Box 1. Innovation Areas for Sustainable Plastics

Manufacturing innovation – e.g. making plastics using chemicals and processes that are inherently less hazardous than current practices. Manufacturing with locally generated waste materials and creating scalable business models; optimizing product design and manufacturing with 3D technology.

Recycling innovation – e.g. developing new technologies to recycle plastics that are not easy to recycle. Agilyx uses pyrolysis to convert polystyrene back into styrene monomer and other base chemicals; GreenMantra Technologies uses thermocatalysis to turn plastics into waxes for asphalt roads and roofs; and into additives for plastics, adhesives and coatings; Jiwen Zhang of Washington State University developed mild catalytic processes to break down ester linkages in amine-cured epoxy resins, a type of thermoset common in composite materials; he recovered carbon fiber and non-crosslinked oligomers from the resin, demonstrating the feasibility of thermoset chemical recycling; Chemical recycling is particularly promising because it is not limited by loss of quality.

Materials innovation – e.g. designing polymers with recycling in mind. Vitrimers are a class of thermosets with cross-linking bonds that form and break depending on temperature, similar to plastics that can be heated and reformed. Polymers can be designed to be unstable (self-immolative), with an end cap that can be removed by exposure to certain forms of light, chemicals or pH conditions, causing the polymer to depolymerize. Monomers can be designed to produce chemically recyclable polymers. For example, ring-opening polymerization can be used to make polymers that can be readily converted back to the original monomer.

Design innovation - designing products based on innovative business models using tried and true existing plastics that do not contain toxic chemicals and that can be readily recycled in most geographic regions; or taking a chance with new materials to demonstrate leadership, create demand, and to drive down costs.

This report was prepared with a broad audience in mind; however, the primary audience is product designers who select plastics for use in products. Decisions are made at the design stage that have long-term sustainability implications. Ideally, the designer is part of a team that informs the sustainable product design process through different perspectives and knowledge of different aspects of the supply chain. This report is also relevant to policymakers and those who procure products and considers plastics in products broadly. It is not limited to any plastic or product types, or geographical regions. The goal is to identify and describe considerations and criteria that define sustainable plastics from the chemicals perspective. Future work to refine the criteria based on material types, product types, intended durability and longevity, and the diversity of cultural practices and material management infrastructures worldwide would be valuable.

Two premises fundamental to this report are 1) there is no one sustainable plastic and 2) a plastic may not be considered sustainable outside of its product use. However, it is possible to establish criteria for plastics that are not sustainable. For example, non-recyclable plastics containing highly toxic chemicals to which workers, users, recyclers or the environment may be exposed, should not be considered sustainable, even if they serve useful functions. Otherwise, the focus of this report is on comprehensive and meaningful criteria that can be used to evaluate plastics and inform decision-making. The chemicals perspective is emphasized in order to reinforce the importance of addressing chemical impacts and toxicity in facilitating a sustainable circular economy.

Sustainable product design is an iterative process of continual improvement (Figure 1). Initially, the product design team establishes design goals using life cycle thinking. The designers then gather information and evaluate the plastics for considerations and criteria related to each life cycle stage including:

1. Selecting feedstock
2. Production and manufacturing
3. Product use
4. End-of-use management

After evaluating criteria at each life cycle stage, the design team is then encouraged to consider the product as a whole and benchmark it against other products providing the same service. This step ensures balance between improvements at one life cycle stage and overall benefits across the full life cycle, and helps drive innovation and not just incremental improvements. The design team next evaluates the information gathered and looks for opportunities to optimize the product against sustainable product design principles. This may involve changes in chemical or material selection, product design, or even a business model, resulting in the need to iterate and to revisit product design goals and re-evaluate impacts and criteria at each life cycle stage. A holistic and principle-based approach to product design helps to drive both incremental improvements and disruptive innovations as both are needed.

Figure 1. Steps to sustainable plastic design and continual improvement

Tools: (1) Chemical Inventory (2) Chemical Hazard Assessment
(3) Exposure Assessment (4) Life Cycle Considerations (5) Decision Analysis

The time needed to implement this framework depends on the type of product and its sustainability attributes. A first pass can be done quickly using screening approaches. For a deeper analysis, more time and resources will be needed to gather data and apply different assessment tools.

This report does not attempt to address all elements of sustainability. It does not include engineering performance specifications, regulatory requirements, market requirements social impact assessment, stakeholder engagement, or consideration of cost and availability. Nor does it compare plastic and non-plastic materials. These elements are important for product design and future work is recommended to integrate them into the overarching approach.

2. Establish Sustainable Product Design Goals

2.1. Goals

Establish sustainable product design goals based on life cycle thinking to guide material selection.

2.2. Considerations

The choice of a plastic material is tied to its intended function. Plastics are used in thousands of applications in sectors such as agriculture, footwear and apparel, toys, flooring, medical devices, packaging, etc. Before evaluating materials for chemistry-related sustainability criteria, the design team first defines their product requirements and sustainability goals using life cycle thinking. Product designers initially consider the intended product application(s) and set technical, economic and market requirements. Different applications require plastics with very different characteristics (e.g. flexible, rigid, etc.). Cost, availability and technical engineering requirements are outside the scope of this report and are set by the design team during product scoping. Once these requirements are met, the most sustainable solutions are sought.

Market requirements can be linked to sustainability and drive plastic selection. Examples include compliance with ecolabels, certification programs, procurement specifications, and industry sector voluntary initiatives. Some certification programs restrict the use of specific polymers (e.g. polyvinyl chloride (PVC)) or additives (e.g. brominated flame retardants). In the apparel and footwear sector, Zero Discharge of Hazardous Chemicals programme participants agree to avoid intentionally using chemicals on their Manufacturing Restricted Substances List (MRSL).

The intended product durability and longevity influences the requirements for the plastic. Using a durable plastic in a long lasting product will have life cycle benefits. Durable plastics in short-lived applications may or may not have benefits, depending on whether or not it facilitates reuse and recycling. For example, food takeout containers are typically single-use, disposable and made from lightweight plastics such as polypropylene, polystyrene or polylactic acid. While technically recyclable, most food-contaminated plastics are not recycled. In contrast, Go Boxes made from polypropylene are sufficiently durable for collection, washing and multiple reuses.[10] Future work is recommended to determine if considerations and criteria are different for plastics in durable versus non-durable goods, especially where reuse is not viable.

Designers should consider overall design objectives at each life cycle stage. For example, a designer may prefer biobased or recycled plastics as feedstock. A designer may seek to reduce a product's carbon footprint relative to competitive products during production and manufacturing. Based on intended (and unintended) product uses, designers may prioritize considerations for certain hazards and exposures. For instance, a manufacturer may prioritize plastics that contain chemicals benign to the skin for plastics used in wearable devices. And a designer should plan for the product at its end of use. For example, the product could be designed for recycling within either an existing public recycling infrastructure, or for a product stewardship or 'take-back' program.

It is useful to decide up front how material selection decisions will be made. A decision method can dictate information needs and how the criteria will be applied as the design moves forward. For example, some criteria can be strict cut-offs. If a material does not meet these criteria, it is eliminated from further consideration.

Box 2. Life Cycle Thinking

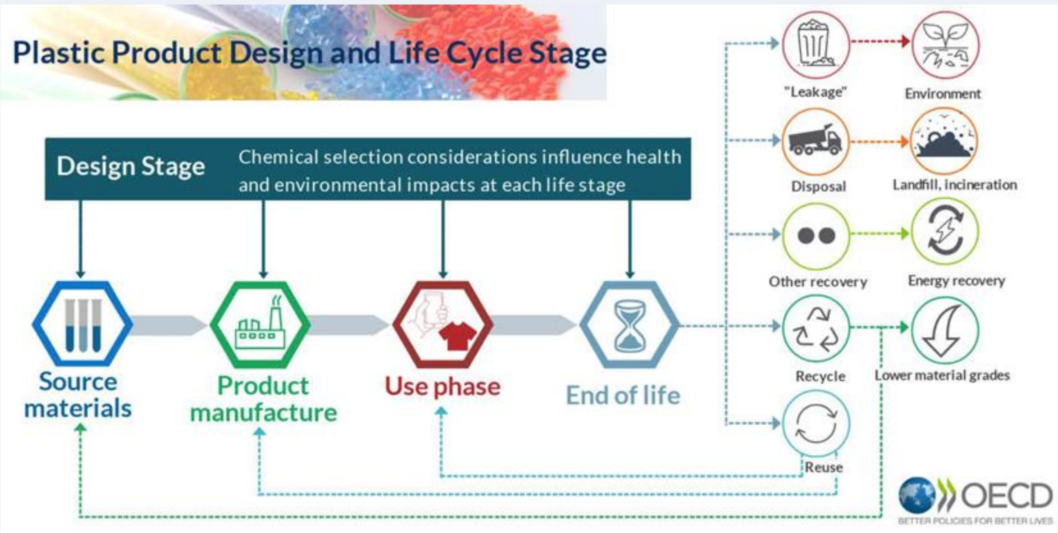


Figure 2. Plastic Product Design and Life Cycle Stage[11]

Life cycle thinking (LCT) considers potential impacts from a plastic product across its life cycle. It helps with problem scoping and informs all sustainability considerations. The key aim of LCT is to identify life cycle stages where significant impacts occur and highlight differences between alternatives. LCT avoids burden shifting by identifying where changes at one life cycle stage, in one geographic region or in one impact category result in increased impacts elsewhere. LCT allows manufacturers and policy makers to identify opportunities for improvements across the supply chain and through all the product life cycle stages and identifies those life cycle segments where significant impacts or significant differences occur. More information on LCT can be found in the Interstate Chemicals Clearinghouse (IC2) and the California Safer Consumer Products alternatives assessment guides.[12,13] Mapping the plastic product's life cycle stages supports LCT and provides a comprehensive approach to meet sustainable product design goals.

In contrast to LCT, life cycle assessment (LCA) provides quantitative assessment of differences between materials for a set of impact categories. LCA accounts for impacts across the entire product life cycle or can be scoped more narrowly to address certain life cycle stages and impacts. LCT can identify those life cycle stages where meaningful differences are likely to occur between alternative plastics, and where more expertise, data and analysis using LCA will be most fruitful. LCA is particularly useful when accounting for energy, water and materials use across a product's life cycle. It does not assess impacts from toxic chemical exposure to workers, consumers, recyclers or the environment nor does it address waste issues such as marine litter. Sustainable design principles are needed to supplement LCA to ensure that chemical toxicity, exposure and waste/circularity are considered. More information on LCA is found in Appendix 1.

2.3. Example criteria

Establishing sustainable product design criteria is part of scoping and depends primarily on the design teams goals and values. Use of a checklist is recommended. The design goals should address 1) all of the sustainable design principles, 2) each life cycle stage and 3) how decision-making will be made.

2.4. Challenges and Tradeoffs

Some decision-making approaches are simpler than others, use fewer resources and cost less. Three distinct decision methodologies have been defined in the alternatives assessment (AA) process (Appendix 2), the Sequential, Simultaneous and Hybrid Methods. In general, the Sequential Method eliminates options that fail individual design criteria in a step-by-step process. The Simultaneous Method is more comprehensive, more difficult to implement, and requires more data. A process of elimination is not used. Rather, data are collected for all considerations and criteria and alternatives are evaluated simultaneously using a multi-criteria decision analysis approach. A hybrid approach eliminates options that fail high priority design goals (e.g. 'showstoppers') using the Sequential Method, and compares remaining options using the Simultaneous Method.

3. Feedstock Considerations

3.1. Goals

Select plastics based on feedstocks that preserve natural capital (maximize resource efficiency) and provide performance and sustainability benefits.

3.2. Considerations

According to the World Forum on Natural Capital, natural capital is defined as the world's stocks of natural assets that include geology, soil, air, water and all living things.[14] Humans depend on natural capital for a wide range of ecosystem services. Poorly managed natural capital can destroy productivity and resilience, making it difficult for humans and other species to sustain themselves. Sustainable product design principles emphasize the preservation of natural capital (and resource efficiency) as an imperative. The choice of plastic feedstock is linked to impacts on natural capital. The goal is to decouple feedstock selection from negative impacts on natural (and societal) capital. Plastics based on 1) non-renewable, non-recycled resources, 2) feedstock that degrades or consumes renewable resources faster than they can regenerate, or 3) materials that degrade the environment or compete with food production are not sustainable feedstocks.

First, the primary feedstock used to generate the plastic is identified. Using feedstocks from recycled materials and readily recyclable plastics links upstream material selection to downstream recycling options. In general, rapidly renewable biomass or readily available agricultural wastes have benefits at the feedstock life cycle stage. However, they require special attention to manage during product disposal/recycling if they cannot be recycled with more conventional plastics. They risk contaminating recycling streams and thereby lowering recycling rates. Rapidly renewable feedstocks include quick growing land-based or water-based crops such as algae or seaweed. Preferred materials avoid using land that competes with social, ecological or food production on the local, regional and global scale.

Waste-derived materials include agricultural wastes or recycled material of sufficient purity that can be re-recycled without loss of performance and without the propagation of toxic chemicals. Sustainability is enhanced by linking waste products to feedstock to ensure both supply and demand for materials that cycle in a sustainably managed material economy.

LCA measures impacts from materials, energy and emissions associated with a feedstock. While rapidly renewable, waste-derived feedstocks are intuitively beneficial, assumptions should be checked. Biomass grown with extensive use of pesticides, energy and water may not offer life cycle benefits. Additional tools for assessing impacts from feedstock selection include product social impact[15] and natural capital[16] assessments.

3.3. Example criteria

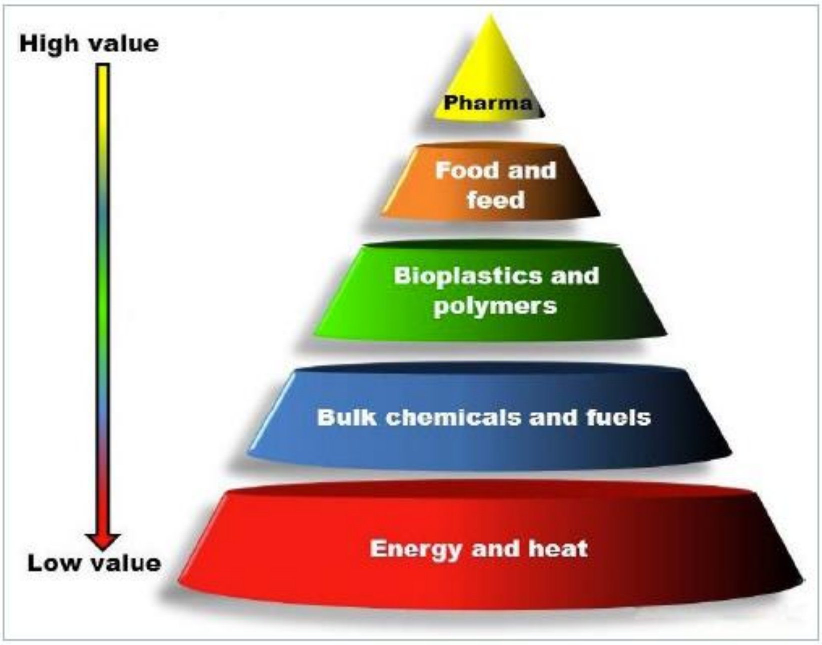
Plastic products can be compared based on the percent (by weight or volume) of materials made from 1) rapidly renewable feedstock, 2) waste-derived materials, and/or 3) readily recyclable plastics. Plastics derived from non-renewable feedstock support sustainable materials management as long as product design facilitates future recycling and ongoing use of recycled materials.[17] Evidence of highly efficient recycling infrastructure should be documented before selecting plastics derived from non-renewable or recycled resources.

3.4. Challenges and Tradeoffs

Resource extraction may impact local communities. Tools for assessing impacts on communities and their natural capital have been developed but are outside of the scope of this report. Future work to integrate these concepts into this framework is recommended.

Biobased feedstock should not compete with "higher' uses (i.e. social, ecological or food production value on the local, regional and/or global scale). The Biomass Value Pyramid in Figure 3 depicts a cascading approach to preferred biomass use with the highest priority given to the uses at the top of the pyramid.[18]

Figure 3. The Biomass Value Pyramid



Source: Peter Westermann, taken from Lange *et al.* (2012: 88)

The availability of recycling infrastructure varies globally and, therefore, so does the availability of recycled feedstock. Choosing recycled plastics can be challenging because information is often lacking on the chemicals in the plastics. Previous use cycles may have included toxic additives or other additives that are undesirable for the next use cycle. Information also is lacking on how well different plastics undergo multiple cycles.

4. Production and Manufacturing

4.1. Goals

Produce and manufacture plastics products in a way that maximizes resource efficiency and eliminates toxic chemicals and pollution in order to protect workers, the community around the production or manufacturing facility, and the environment.

4.2. Considerations

Ideally the product designer will know 1) the unit processes that make up production and manufacturing, 2) the chemicals used and produced in each unit process, 3) the hazard profiles for those chemicals and information on 4) potential exposures to workers and the surrounding community and environment. Chemicals used in production and manufacturing may not be intended as ingredients but may find their way into the final product as residuals and impurities.

Data on energy consumption (amount and source of energy), water and overall waste produced are also useful in order to compare options for life cycle impacts.

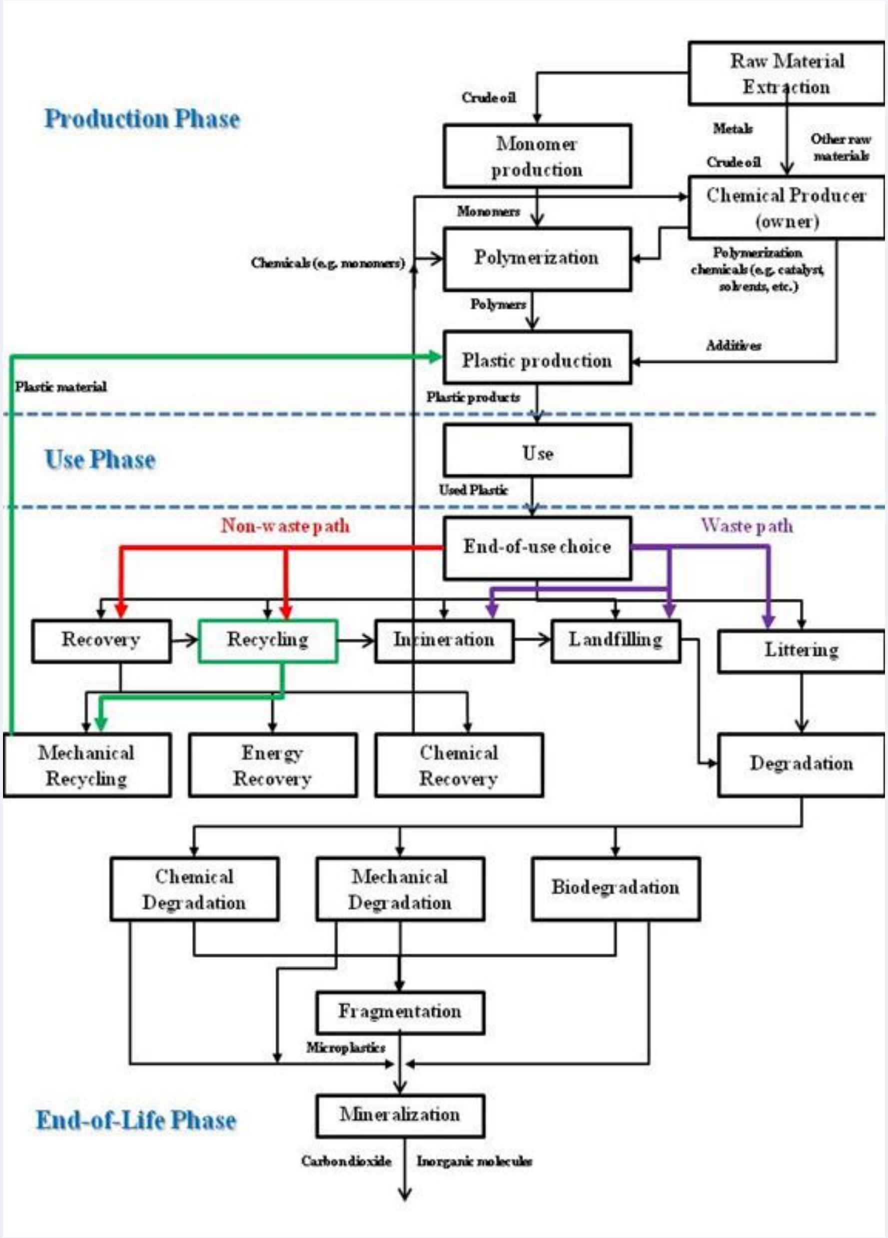
Unit Processes in the life cycle of a plastic product. Production and manufacturing are comprised of unit processes within life cycle stages spread across the supply chain, as illustrated in Box 3. Mapping the unit processes used to make a plastic material and/or plastic product is a useful first step to understanding the supply chain.

Life cycle inventory databases can assist in identifying generic chemical and materials inputs and outputs in support of the chemical inventory. However, deviations from generic production need process specific information.

Chemical inventory. At a minimum, the chemical inventory includes all substances relevant to occupational exposures and/or that are likely to be retained in, or migrate from, the plastic. This includes the monomer(s), oligomer(s) and any known additives and residuals (impurities). Chemicals must be identified before they can be evaluated. Chemical inventory and disclosure is a key information need. See Box 4.

The types of chemicals commonly used or generated in the production and manufacture of a plastic material are defined by the function the chemical performs. Common chemical types include raw materials, monomers, oligomers, catalysts, polymer, performance additives (anti-oxidants, colorants, plasticizers, UV stabilizers, flame retardants, compatibilizers, etc.) and manufacturing and processing aids (solvents, auxiliaries, lubricants, mold release agents, cross-linkers.

Box 3. Key Information Needs: Example Unit Processes in the Life Cycle of a Plastic Product (modified from Lithner.[19])



Box 4. Key Information Needs: Chemical Inventory and Disclosure

Inventorying chemicals across the life cycle. Chemicals used and generated across the plastic's life cycle are identified in order to assess hazard, exposure, life cycle and disposal/recycling impacts. Assembling a complete chemical inventory for each life cycle stage can be challenging because formulations are often proprietary, and information for all life cycle stages may not be available, even to manufacturers throughout the supply chain.

It is important to be aware of existing legal requirements for hazardous chemical disclosure in plastics such as those specified in REACH Article 33 or the EU Waste Framework Directive.

Chemical identification. Most chemicals have multiple names and need to be identified clearly using conventions such as Chemical Abstract Services numbers (CASRN), International Union of Pure and Applied Chemistry numbers (IUPAC) and others (EINECs, INCI). In theory, these identifiers are unique. However, some identifiers apply to general classes or groups of chemicals and more nuanced identification may be needed, such as for different forms of a chemical or molecular weight ranges. Additional data such as molecular structure and physical form help to refine the compound's identity. The chemical inventory includes the precise chemical identity, the chemical function, and concentrations or amounts (estimates or ranges).

Disclosure requirements. Clear thresholds are needed to determine which chemicals to include in the inventory and which to assess. One strategy sets a concentration threshold or de minimis level at or above which a chemical constituent will be evaluated. Selecting a threshold may depend in part on the chemical's hazard characteristics. For example, endocrine disrupting substances are hazardous at very low exposure levels and thus a low threshold is appropriate. Safety Data Sheets provide precedent for using different disclosure levels for chemicals with different hazard traits. Carcinogenic chemicals above 0.1% must be reported while non-carcinogenic hazardous chemicals are disclosed above 1%.[20] Some certification programs (e.g. Cradle to Cradle) link certification levels to the weight percent of chemicals disclosed. Example disclosure thresholds include:

- All intentionally used or added chemicals at any concentration at all life cycle stages.
- All intentionally used or added chemicals at any concentration for limited life cycle stages (e.g. use phase only).
- All intentionally added chemicals plus residuals at or above a concentration threshold[21].
- All chemicals and residuals present at or above a concentration threshold.
- Specific chemicals known NOT be present in a product.

Transparency. Perfect information is not possible and there is no one single right way to set disclosure requirements. Transparency is important because information about what is known, and not known, about the chemicals used in production and manufacturing will support informed decision-making. Some people use a tiered and iterative approach to inventorying chemicals, starting with higher disclosure thresholds, and working to gather additional information at lower thresholds as feasible and relevant.

Chemical hazard assessment (CHA). (Box 5) Understanding the hazard traits of chemicals used in plastic production and manufacture is necessary for informed decision-making. Hazard assessments can be performed at varying levels of depth and complexity. The design team will select the level of chemical hazard evaluation and the assessment method to be used. Each method dictates its own data requirements. Several hazard assessment tools exist. The OECD created the Substitution and Alternatives Assessment Tool Selector.[22] Using this selector, designers can evaluate the hazard assessment tools available and determine which tool best suits their needs. The California Safer Consumer Products Alternatives Analysis Guidance Manual also provides a comprehensive list of CHA methods and databases.[23]

Exposure assessment. (Box 6) Comparative exposure mapping helps identify potential exposure pathways. Exposure measurement is not needed in most cases. Rather, qualitative exposure assessment can be based on the chemical presence in a form that can be inhaled, ingested or absorbed through the skin. Occupational exposures to hazardous chemicals and toxic emissions and waste during production and manufacturing should be prioritized.

4.3. Example Criteria

- Prefer plastic materials made via chemical processes that minimize the use of and exposure to hazardous substances. Plastics can be compared based on analysis using tools such as ProScale. ProScale provides metrics for comparing products for human health hazards and exposure to toxic chemicals during production and manufacturing.[24]
- Plastic production can also be compared based on analysis using tools designed for occupational safety and health such as the NIOSH Exposure Banding Process: Guidance for the Evaluation of Chemical Hazards[25], or Control of Substances Hazardous to Health (COSHH) Essentials.[26] These tools identify chemicals of high concern to workers based the inherent hazard traits of the chemical, the chemical form and exposure routes.
- Maximizing resource efficiency requires measuring energy and water consumption, materials used and waste generated in order to benchmark a product against other products and to guide efficiency improvements. Resource efficiency during production and manufacturing can be measured using standard life cycle assessment tools.

4.4. Challenges and Tradeoffs

It can be very challenging to access information on production processes, the exact identification of chemicals used and produced, and where exposures occur. The ability to obtain information may depend on one's sphere of influence and position in the supply chain. At a minimum, an assessment of production and manufacturing should include all substances that are relevant to occupational exposures and emissions from a production or manufacturing facility.

Supply chain collaboration and transparency allows for 1) prioritizing information needs and 2) sharing information, even under confidentiality terms. In the automotive sector, the Global Automotive Declarable Substance List (GADSL) was developed through collaboration between the automotive, automotive parts, and chemical/plastics industries.[27] GADSL facilitates communication and exchange of information on substances used in automotive products through the supply chain. The GADSL focuses only on those substances that are expected to be present in a material or part in a vehicle when sold. Previously, companies created different declarable substance lists. Their experience prompted creation of a single globally harmonized list with clear criteria and transparent process for maintenance.

Products produced with chemicals that have lower hazard and lower likelihood of exposure should be preferred. While resource efficiency is important and frequently has direct economic implications (e.g. energy consumption), it is important that designers consider resource efficiency metrics separately from metrics that address exposure to human health or environmental hazards. They are linked to different sustainable design principles and should not be aggregated.

5. Product Use

5.1. Goals

Eliminate hazardous chemicals used in plastic products, and pollution and waste associated with product use.

5.2. Considerations

Ideally the product designer will know 1) the chemicals retained in the plastic material, 2) the hazard profiles for each chemical including the polymer substance itself 3) relevant exposure information such as quantities, exposure routes, leaching potential, etc. 4) wastes or pollution generated during product use, and 5) key data gaps.

Use phase chemical inventory. Plastics are typically mixtures of chemicals that include the polymeric substance, residual monomers and oligomers, catalysts, additives, residual reagents and manufacturing or processing aids and other impurities. The design team prioritizes which constituent types (e.g. monomer, catalyst, additives) need to be identified and at what concentration thresholds. For example, only chemical constituents above 100 ppm may be identified for chemical hazard assessment.

Chemical hazard assessment (CHA). Ideally, comprehensive CHA reports would be readily available for every chemical; however, this is rarely the case. A pragmatic approach involves searching for existing publicly available comprehensive CHAs such as those found in the Interstate Chemicals Clearinghouse Chemical Hazard Assessment Database.[28] If no CHA exists, hazard list screening of the chemical followed by intermediate CHA screening may be informative. If results from intermediate screening are not definitive, the design team can conduct a more detailed assessment using all available literature. A full CHA provides information not only on what is known, but also on what is not known, specifically about chemical hazards and data gaps.

Box 5. Key Information Needs: Chemical Hazard Assessment (CHA)

Understanding the hazard profiles of plastics and their chemical constituents is necessary for informed decision-making. CHAs can be performed at varying levels of depth and complexity. As a first step, the CHA level and the assessment method used are determined. Several hazard assessment tools exist and each dictates its own data requirements. The OECD created a Substitution and Alternatives Assessment Tool Selector[29] that designers can use to evaluate available CHA tools and determine which tool best suit their needs. The California Safe Consumer Products Alternatives Analysis Guide also provides a comprehensive list of CHA methods and databases.[30]

Classify Individual Chemical Hazards. CHA methods range from a basic hazard list screening evaluation to detailed and comprehensive evaluation. CHAs differ based on both the number of hazard endpoints and the depth to which each endpoint is evaluated. With increased CHA depth comes increased understanding of each chemical's potential impacts to human health and the environment, and better knowledge of data gaps. However, increased depth of assessment also requires more data, time, expertise and cost. One challenge of CHA is that results may vary depending on who does the work because reasonable toxicologists can disagree, and different countries may use different data sets. This is true for all of the methodologies unless conflicts are resolved by authoritative oversight.

Full CHAs. Full CHAs require expert review and interpretation of the scientific literature. When chemical data are lacking, compounds with structural similarities can be used as surrogates using read-across methods. Computer modeling based on mechanisms of action and structure-activity relationships has improved in recent years with the implementation of the European Union's REACH program which de-emphasizes animal testing and fosters development of alternative testing schemes. Emerging hazard screening protocols include high throughput screening such as the USEPA's Tox 21 program.[31]

Standardized CHA methods typically include and expand upon classifications defined in the Globally Harmonised System of Classification and Labeling (GHS).[32] Methods like the USEPA Design for the Environment Program (DfE) Alternatives Assessment,[33] GreenScreen for Safer Chemicals (GS)[34] and Cradle to Cradle (C2C)[35] incorporate GHS hazard endpoints. Full details of these CHA methodologies are available on the parent organizations' websites. These methods expand upon GHS requirements by including neurotoxicity impacts as a unique endpoint and adding stand-alone criteria for persistence (P), bioaccumulation potential (B) and endocrine disruption (EDC).

Appendix 3 provides a list of hazard endpoints typically included in comprehensive CHAs. The California Environmental Protection Agency (CalEPA) provides an even more comprehensive set of hazard endpoints in their Safer Consumer Products program.[36] CHA reports typically present hazard data and hazard classification results in a summary table, and in some cases provide an overall chemical benchmark score.[37] The USEPA DfE Alternatives Assessment method classifies hazards as High/Medium/Low (and sometimes very High and very Low) using colors (Red/Yellow/Green) to indicate hazard levels and bold versus italic fonts to indicate levels of confidence in the determination. The USEPA DfE Program produced the hazard table in Appendix 4 to compare flame retardant alternatives to decabromodiphenyl ether (DecaBDE)[38]. The GreenScreen method is based on GHS and the USEPA DfE methods. It adds an overall chemical (including polymer substances) Benchmark score to facilitate decision-making. See Appendix 5.

Intermediate CHA. Intermediate CHA methods limit the number of hazard endpoints evaluated and data sources. The Quick Chemical Assessment Tool (QCAT)[39] developed by the Washington State Department of Ecology is designed for small and medium enterprises with limited toxicological expertise and resources.

Hazard list screening. As an alternative to these more comprehensive methods, screening chemicals against regulatory and authoritative chemicals lists with known or suspected hazards can be a useful initial chemical hazard evaluation. List screening requires less time and expertise. Hazard lists include publicly available hazard classifications (i.e. H Phrases), lists from authoritative bodies such as the International Agency for Research on Cancer (IARC), etc. Several software tools now facilitate screening chemicals against these approved lists. The Chemical Hazard Data Commons (sponsored by the Healthy Building

Network and powered by their Pharos chemical database)[40,41] incorporates all lists used in the GS List Translator, the ChemSec Substitute It Now (SIN) list,[42] and restricted substance lists (RSLs) and manufacturing RSLs (MRSLs) developed by different industry sectors. If a chemical is not on found on these combined hazard lists, it does not necessarily mean it is safe. The chemical may not have been tested or studied.

Polymers of low concern considerations. The United States, the European Union and others have established criteria and methods to screen for polymers of low concern.43 Polymers are generally unreactive, and their large size prevents them from crossing biological membranes. Hazards associated with polymers are usually tied to non-polymeric substances within the polymeric matrix including unreacted monomers, partially reacted oligomers, additives, etc. Therefore, it is important to know the molecular weight ranges of substances in a plastic including residual monomers and oligomers. Lower molecular weight substances are more likely to migrate from plastic and, if toxic, will result in exposure. Typical thresholds are < 500, > 500 but < 1,000, > 1,000 but < 5,000, > 5,000 and < 10,000, > 10,000 Daltons. These thresholds are for screening purposes and cut off ranges may be shifted if warranted. For instance, ranges may be different for fluoropolymers (< 1,500 Da) or for higher molecular weight substances if accompanied by permeation enhancing substances commonly found in food contact materials.[44]

Criteria for polymers of low concern are intended to protect human health and the environment from the regulatory perspective; however, they do not address sustainability criteria such as feedstock or disposal and recycling considerations. Nor do they address problematic plastic uses such as microbeads directly released into wastewater. The criteria typically address inherent polymer substance toxicity and reactivity relevant to human health and the environment. Example national criteria for polymers of low concern including hazard requirements for sustainable plastics are compiled in Table 1.[45] The USEPA provides an example template for collecting information on polymers (Appendix 6).

Table 5.1. Polymer of Low Concern Considerations[46]

Information on polymer health and environmental hazards	Including hazard classification according to the UN GHS or any relevant national legislation and/or toxicity results from polymer tests.
Polymer class	Work by the OECD[47] indicates polymers belonging to specific chemical classes are potentially hazardous; namely polyacrylates, polyurethanes, polyvinyls, epoxy resins and polyacrylonitriles. These polymers are considered potentially hazardous because of the presence of unreacted toxic monomers (e.g. vinyl chloride or isocyanate). However, no reliable systematic correlation has been established between polymer class and hazard. Only polyesters using pre-approved chemicals are considered polymers of low concern.
Presence of residual monomers	Polymerization reactions rarely proceed to 100% completion, leading to the presence of unreacted residual monomers and oligomers.
Low average molecular weight and oligomer content	Polymers with smaller average molecular weights are more likely to cross biological membranes and are considered more likely to be hazardous. Polymers with MW = 1000 Daltons (Da) are more likely to pose health and environmental concerns. Therefore, the presence of oligomers increases the probability of it being hazardous, as oligomers

	can migrate from the polymeric material to biological media. Polymer intermediates intended for future polymerization are expected to contain higher levels of unreacted monomers and oligomers. The USEPA Safer Choice Program typically applies its hazard screening criteria to the low molecular weight components of polymers (less than 1,000 Da).[48] Reporting is required for: • Number-average molecular weight (Mn) • Weight-average molecular weight • Molecular weight distribution ranges (Da) including: <500, >500 but < 1,000, >1,000 but <5,000, >5,000 and <10,000, >10,000 • W% of polymer components below 1,000 absolute molecular weight
Presence and content of reactive functional groups (RFG)	Polymer toxicity can be caused by the presence of reactive functional groups at the surface of the polymer material. Alkylating agents that bind with and denature DNA and/or protein and electrophilic groups that damage DNA are of greatest concern. Report equivalent weight of reactive functional groups including acrylates, isocyanates, aziridines, hydrazines and vinyl sulfones.
Special properties	Cationicity: Cationic polymers have attributes that raise concerns for aquatic toxicity and inhalation health effects (i.e. cationic charge density) Water absorption: Polymers that absorb a lot of water (i.e. their own weight in water) have been found to raise concerns for carcinogenicity.

Evaluating Mixtures and Polymeric Materials. CHA methods provide insight into the hazards of individual chemicals (and polymer substances). But plastics are polymeric materials, i.e. compounded mixtures of a polymer substance and intentionally added constituents, residuals or impurities. A limited number of methods exist to evaluate the hazards of polymeric materials. In several regulatory systems, polymer hazards are tied to low molecular weight compounds that leach from the bulk polymer or are present at or above a concentration threshold such as 1%. This implies there is a direct toxicity link between monomers and toxicity of the overall plastic.[49] Under REACH, it was estimated that between 30% and 50% of all polymers registered may have properties that would require classification as hazardous for human health or the environment.[50] An OECD Task Force study supported this conclusion.[51] Knowing the concentration and toxicity of residual monomers can help distinguish between plastics based on hazard. However, other chemical additives could dominate the plastic hazard profile.

Several standardized approaches to evaluating the hazards of polymer substances and polymeric materials exist. GHS provides rules for classifying chemical mixtures that can be applied to polymers. GHS allows a mixture to be ‘not classified’ (low hazard) if it is shown conclusively the substance or mixture is not biologically available with experimental data from internationally acceptable test methods. Alternatively, individual ingredients may be classified for hazard and an algorithm used to calculate an overall hazard classification. The C2C Product Certification program evaluates polymers based on their toxicity and evaluates products against criteria in five modules: Material Health, Material Reutilization, Renewable Energy & Carbon Management, Water Stewardship and Social Fairness. While overall product certification is based on all five modules, the Material Health module can be used as a standalone method.[52] Based on USEPA's Sustainable Futures Program, the USEPA Safer Choice Polymer Screen provides guidance on how to evaluate polymeric substances and their degradation products for potential impacts to human health and the environment.[53] A polymer is assumed to be a safer alternative if it passes all requirements. GreenScreen v1.4[54] scores polymer substances in combination with monomers and catalysts used during manufacture. The Plastics Scorecard scores polymeric materials by evaluating individual chemicals and aggregating their associated GreenScreen Benchmark scores. [55]

A product designer may customize an approach to compare plastics based on the hazards of substances in the plastic. For example, plastics may be prioritized if they do not contain substances of very high concern (SVHCs) or substances found on sector-based RSLs. Alternatively, plastics with specific hazards relevant to the product design may be eliminated. For example, chemical additives that cause skin sensitization would be undesirable in plastics with prolonged dermal contact. The electronics giant Apple simulates sweat to extract chemicals from plastics intended for use in their wearable devices.[56] Extracted chemicals can be identified and evaluated independently, or tested directly for toxicity. Toxicological testing of food contact materials is primarily focused on single substance and limited toxicological endpoints. However, regulation requires substances migrating from food contact materials to undergo risk assessment. In many cases, the migrating substances may not be known. Methods are being developed to extract chemicals from food contact materials and to test them with rapid and cost-effective bioassays. These bioassays typically use cell cultures, crustacean larvae or zebra fish embryos to assess cytotoxicity, genotoxicity and/or endocrine disruption.[57]

Additives. There are dozens of additive functions and many chemicals that fill each additive function.[58] In addition to performance requirements, additives include colorants, fillers, and fiber. Some polymers need more additives than others to meet performance requirements.

Many well-known toxic additives and/or constituents exist in consumer products and plastic packaging. Examples include certain phthalates, certain flame retardants, bisphenol A, heavy metals (i.e. Cd, Pb, etc.), biocides (arsenic compounds; organotins; triclosan, etc.), and highly fluorinated substances such as mold release agents. Oxo-degradable additives are also problematic. They accelerate the fragmentation of plastic into microplastics but do not increase biodegradation of inert plastics, and may also adversely impact recycling.

Exposure considerations. Exposure to chemicals in plastics depends on the properties of the plastic, its chemical constituents and how those constituents are integrated into the plastic.[59] Not all plastics will result in the same exposure scenarios. It is important to include potential human health and environmental exposures in the assessment. See Box 6. An example template for comparing chemicals for exposure considerations is in Appendix 7.

Box 6. Key Information Needs: Comparative Exposure Assessment[60]

A conceptual model or map of potential exposures across the product life cycle is used in risk assessment. Using this map, assessors identify where exposure to chemical ingredients or degradation products are most likely to occur and to whom. Susceptible individuals or populations and environmental receptors should be identified along with the most likely routes of exposure (oral, dermal, inhalation). Environmental fate and transport through, air, water, soil, sediment, etc. as well as exposures resulting from waste disposal and treatment should be considered. Both intentional and reasonably anticipated exposure scenarios, even if the product is not designed for specific uses, should be addressed (see Appendix 8 for example Exposure Map (Greggs et al.) [61].

Evaluate ingredient/product interactions.

- Concentration in the plastic and the frequency of product use that can impact exposure.
- Intended use and reasonably anticipated misuse (e.g. children mouthing) of the product dictates exposure potential. In some cases, extractability and leachability testing is recommended to assess exposure potential to plastic contents, especially food contact plastics.
- Some plastics and their corresponding additives are more prone to migration than others. Consider both the permeability of the plastic and how the additive is incorporated.[62,63]
- Environmental parameters, such as the temperature at which the product is used, can affect the plastic migration rates and plastic degradation pathways. Product wear also impacts the exposure potential of plastic constituents.
- Unreacted monomers or partially reacted polymers intended for further polymerization may result in higher exposure. For example, 3D printing using stereo lithography may result in higher monomer exposures.

Evaluate inherent chemical properties.

Chemical ingredients have different inherent chemical properties that affect exposure potential such as volatility, water solubility, reactivity, etc.[64] A comprehensive CHA includes some physical properties such as the octanol-water partition coefficient and persistence in various environmental media. The following inherent properties can be integrated into exposure criteria:

- **Bioavailability**: Ability of a substance to be absorbed and circulated in an organism (e.g. skin permeability, oral absorption).
- **Bioconcentration or bioaccumulation factor (BCF, BAF)**: Direct measurement of whether a chemical is bioconcentrating or bioaccumulating indicating increased exposure potential, primarily from food and the environment.
- **Aqueous solubility**: Greater potential exposure through aqueous media.

- **Octanol-water partition coefficient (log Kow)**: Indication of fat solubility; higher fat solubility suggests greater chance for bioconcentration or bioaccumulation.
- **Persistence**: Resistance to degradation and especially biodegradation suggests greater long-term exposure. Consider persistence in air, fresh and marine water, soil, sediment and in sewage treatment.
- **Melting point**: Melting may increase exposure to chemical in liquid form.
- **Boiling point**: Greater volatilization and potential for inhalation.
- **Vapor pressure**: Greater volatilization and potential for inhalation.
- **Molecular weight**: Smaller molecular weights may increase bioavailability.
- **Henry's Law Constant**: Indicates how much of a chemical escapes into the gas phase. Higher values indicate greater the potential for exposure via inhalation.
- **Particle size distribution**: Tied to potential inhalation exposure, i.e. smaller particles are more likely to penetrate the lungs, skin, etc.
- **Skin permeability, log Kp**: Higher skin permeability may increase dermal exposures
- **Soil sorption partition coefficient (log Koc)**: Greater soil adsorption may suggests less migration and bioavailability and more exposure to soil organisms.
- **Octanol-air partition coefficient (log Koa):** Indicates greater solubility and retention in fats and/or organic matter relative to release to the air.

5.3. Example Criteria

- Polymers (polymer substances) can be compared based on whether they meet regulatory definitions of polymers of low concern and if they contain additives or other substances designated as substances of very high concern (or equivalent) under any legal jurisdiction.
- Prefer plastics that meet performance requirements with no, or few, additives.
- Compare plastic products based on the toxicity of the plastic material. All ingredients present at or above the selected inventory threshold should undergo CHA. Plastics with the least hazardous constituents, particularly where direct exposure to users is likely, should be preferred. Chemicals can be extracted from the plastic and either identified or directly tested for toxicity. Plastics used as food contact materials should be extracted with food simulants to determine which chemicals migrate out.
- With respect to resource efficiency, plastic products can be compared based on quantities of resources used and wastes produced during use and maintenance.

5.4. Challenges and Tradeoffs

It is challenging to obtain sufficient information on chemical constituents in the plastic materials, including exact identity, concentrations and their propensity to migrate from the plastic. Therefore the design team should prioritize information needs based on understanding of the plastic product life cycle.

Comprehensive chemical hazard assessment information on every constituent identified is difficult to obtain. The most comprehensive CHA approaches are preferred, but CHA screening approaches can be used to provide initial assessment of multiple chemicals. Depending on how the plastic is used in a product, test data for specific hazard traits may be necessary (i.e. testing plastics for wearable devices for skin irritation and sensitization). Where data are not available, the design team needs to identify how to fill toxicity data gaps.

In lieu of adequate disclosure in the supply chain, exposure testing may be necessary to identify constituents and/or for direct toxicity assays.

6. Product End of Use Considerations

6.1. Goals

Maximize resource efficiency and eliminate waste, hazards and pollution associated with the fate of plastics after use.

Guide product designers in 'designing for circularity' with consideration of geographic differences.

6.2. Considerations

The choice of plastic for use in a product is a design choice that may determine waste treatment options. Design for circularity means selecting inherently safe materials for use in products that minimize the creation of waste and can be recycled or reused in regions where the plastic product is sold.

Available waste management infrastructure. Different countries and jurisdictions have different product packaging and waste management requirements that should be understood by product manufacturers. These differences vary not only between countries, but even between cities and towns in the same region or country.

Product designers should be cognisant of available waste management infrastructure options wherever the product is sold, including all elements of the waste hierarchy. These include waste prevention, reuse and recycling at the top of the hierarchy, moving to energy recovery and other recovery and disposal (see International Waste Hierarch according to the Integovernmental Panel on Climate Change cited in [65]). Some types of recovery include plastics-to-fuel, chemical recycling and commercial composting.

Besides the availability of waste management infrastructure, the likelihood a plastic product will follow a life-cycle pathway at the top or at the bottom of the waste hierarchy is related to the chemistry of the plastic product, its intended longevity and durability, the quality and value of the recyclate, cultural norms, etc.

The inherent properties of the plastic material enable different disposal and recycling options. Design teams should be knowledgeable about opportunities for reuse and repair to increase product longevity. Keeping plastics from becoming waste is a top priority. Information on the kind(s) of recycling that a plastic can undergo is important. Some chemical recycling technologies are highly material specific (i.e. PET) and produce high quality monomers to create virgin-like plastics. It would also be useful to have an idea of how many cycles a particular plastic product can undergo.

Plastics designed for degradation are informed by knowledge of the plastics' inherent degradability in air, water, soil and sediment and under aerobic and anaerobic conditions, as defined in most chemical hazard assessment persistence classification methodologies. Degradability can also include the ability of the plastic to be composted in commercial or 'backyard' compost operations. Compostability is supported by certification programs such as the harmonized European standard EN 13432, EN 14995 (for non-packaging items), home (backyard) standards such as DIN CERTCO (Germany) and Vinçotte (Belgium). Marine degradability standards also exist such as ASTM D7991. Marine biodegradability could be a desirable feature in a plastic to mitigate a worst-case leakage scenario, but should not be presented as a waste treatment pathway.

In terms of energy or material recovery as a waste pathway, some plastics are processed to polymers or fuel more cleanly and completely than others. PET and PVC appear to be less preferred due to low conversion rates with polystyrene (PS) reaching rates of 80-85% conversion.[66]

Some materials such as composites are not inherently recyclable but may be recyclable in the future. Therefore designing for circularity today means avoiding the use of non-recyclable composites for short-lived product applications.

Impacts of various disposal and recycling options. It is important to understand relative impacts of waste treatment technologies in general, and material-specific impacts associated with the chemistry of a plastic. The waste hierarchy serves as a rough guide to prioritizing waste management paths with waste prevention clearly the top priority. LCA can provide improved accuracy when comparing waste treatment options. For example, from a human health perspective, recycling is the best option with incineration with energy recovery and landfill following.67 From the greenhouse gas perspective, recycling is the best option, followed by > waste to energy, composting, landfill and incineration. [68]

Based on knowledge of the plastic and its constituents, transformation products that form when the plastic undergoes different waste treatment paths can be predicted. Transformation products come from chemical degradation, combustion, mechanical degradation and biodegradation. For example, plastics containing organohalogens will form combustion by-products like HCl, HF and potentially dioxins and furans, under non-ideal conditions. If a food container is commercially compostable and contains a toxic and persistent additive, the additive may not break down, and can contaminate the compost and lower its value. Recycling can have unwanted human health impacts, particularly from the release or accumulation of hazardous chemicals in plastics.

Note that additives do not have to be hazardous to interfere with recycling. Some relatively benign chemicals such as fillers, if present at high enough concentrations, can interfere with recycling and material quality. Older products containing toxic constituents create legacy issues that perpetuate unwanted releases and recyclate contamination, while the markets transition to new plastics.

Potential for beneficial material recovery. It is important to consider whether or not a plastic can be recycled, and if so, how many times and under what conditions. The plastics that are the most energy and resource intensive to make, may have the greatest life cycle benefits when recycled. There is a need to consider carefully the chemicals in the plastic to determine whether or not their presence will lower the value of resulting materials and potential for future cycles due to contamination.

Using product design to minimize waste and chemical hazard, and to maximize recycling. Some plastic products are more likely to be leaked to the environment (e.g. straws versus laptop casings) and some plastic recycling options provide more life cycle benefits (or impacts) than others and result in cleaner and more valuable recyclate. In designing for circularity, the design team should maximize the amount of product that can be recycled and make design or material changes to improve the overall results. The RecyClass Tool[69] developed by Plastics Recyclers Europe guides the choice of plastic in packaging and promotes recycling. The tool requires the packaging to be made of plastic (not mixed with other materials), free of dangerous substances and contain no bio- or oxo-degradable plastics. It also addresses the presence of incompatibilities that affect the efficiency of recycling. Plastics easy to identify and to separate from the rest of the product, and for which there is an established Plastics Recyclers Europe (PRE) recycling stream, score better. This tool is a model for how material selection and product design can be linked to recycling options. A similar tool could be developed to address how to design plastic products to avoid waste and litter generation and to undergo other treatment technologies such as composting. Product design can also be used to maximize the number of possible recycling options and to minimize harm in worst-case leakage scenarios. For example, plastic six-pack beverage rings cause harm to wildlife if leaked into the environment. Innovators have introduced alternatives such as ‘edible plastic rings’ and Paktech six-pack holders.[70]

Product stewardship and communication. Product design should include having a plan for recovering and recycling the plastic after use that accounts for regional differences. The plan may take advantage of publicly accessible waste management infrastructure or it may involve a closed and privately managed materials system based on product stewardship. The product design should be optimized for recovery and recycling of the plastic material and instructions should be detailed, going beyond labels that say ‘please recycle’. For example, Green Blue Institute developed the How2Recycle Labeling program to optimize proper product and recycling management of packaging.[71]

6.3. Example Criteria

Plastics can be compared based on how well the feedstock is linked to recycling options. The following are various criteria that can be considered:

- Choose materials that are recycled and that can be further recycled or choose rapidly renewable biobased plastics that can be used to generate compost.
- Compare materials based on the extent of recycling options available over the geographic regions where the product will be sold.
- Select plastics that can have the best recycling profiles. For example, prefer plastics that can be recycled multiple times, plastics that can be recycled using technologies that have minimal impacts to recyclers, and plastics with multiple options for waste management pathways to allow for variability between regions with different waste management infrastructures and cultural norms.
- Compare materials based on whether or not they contain hazardous chemical constituents or constituents that interfere with recycling. Avoid additives that degrade the quality of recycled plastic. Chemicals of concern in plastics haunt efforts for a circular economy.
- Design products so that plastics are easy to clean and separate for recycling.

- Compare plastic products based on how much waste they will generate, how long the product is expected to be used and whether or not its longevity can be increased.
- While composites have valuable performance properties, they are not currently recyclable and are best used for durable products, not single-use applications.
- Compare products based on how well specific information can be communicated to consumers about what to do with the product after use. Include prominent instructions that raise awareness, minimize confusion, and communicate guidance throughout the supply chain. For example, clearly differentiate between biobased feedstock and biodegradable plastics to consumers.
- Provide information on multiple non-waste paths, and least harmful waste paths appropriate for the area in which the product is sold.
- Compare products based on worst-case waste disposal and recycling scenarios. While no product manufacturer intends their product to become litter, leakage happens. Compare plastic products for impacts if leakage occurs, to minimize harmful impacts.

6.4. Challenges and Tradeoffs

Considerations and criteria for sustainable plastics may vary depending on geographic, regulatory and cultural differences. Some examples of the challenges and tradeoffs are as follows:

- While plastics to fuel sounds less than ideal in geographic regions with both good waste management infrastructure and ready access to fuel, it may have numerous social and environmental benefits in regions lacking both.[72] The development of a local plastics-to-fuel operation in Pune, India is reducing litter and providing fuel for cooking and tractors while displacing the need to cut down trees. While outside the scope of this report, social contexts should be considered.
- Geographic variability raises questions about whether or not manufacturers should be responsible for designing products for worst case, i.e. litter or leakage, scenarios.
- Obtaining reliable information about what is in plastic materials, recycled or otherwise, is a challenge. Toxic constituents create human health and environmental risks and regulatory challenges. Some additives interfere with recycling. It is also unclear how one would evaluate plastics for how well they can undergo multiple recycling cycles.
- Dealing with legacy products, some of which contain chemicals of concern, versus new products containing safer chemicals is also a challenge. Products with highly hazardous or banned chemicals already on the market should be treated separately from newer material streams, and recycling may not be the best option. Tradeoffs between permanent disposal, instead of inclusion in recycling streams will need to be considered.

7. Whole Product Assessment

7.1. Goals

Maximize resource efficiency and eliminate use and generation of toxic chemicals, pollution and waste across the entire life cycle of the product;

Understand hot spots and tradeoffs and drive innovation and not just incremental improvements.

7.2. Considerations

Plastic products should be assessed at each life cycle stage and across the entire product system in order to optimize for all sustainable design principles. Evaluation of each life cycle stage identifies areas where there is room for improvement at each stage. However, it is also important to see how each life cycle stage contributes to overall product impacts. Using sensitivity analysis, the design team should determine which life cycle stages drive the impacts of the overall product system. Evaluation of the whole product system identifies overall product hot spots and stimulates ideas for innovation. For example, consider the selection of plastic materials for food takeout containers. Several types of single-use, disposal food packaging plastics can be compared against each other by evaluating impacts at each life cycle stage including potential for incrementally better waste paths. However, by considering impacts from the whole product perspective, all single-use, disposable options produce waste, regardless of materials used. By considering the service the product provides and focusing on waste as a hot spot, one entrepreneur created the GOBox. GoBox is a reusable plastic food container with an innovative business model. Go Boxes are designed to serve take-out food from food trucks and are currently used in Portland, Oregon and San Francisco, California.[73] The GOBox plastic is made of lightweight, durable and recyclable polyethylene. Lightweight is important because bicycles are used for their transportation. Durability maximizes the number of times they can be washed and reused and their size and shape need to be familiar to food vendors. Polyethylene plastic best fit the requirements. Food truck vendors commit to using GoBoxes. GoBoxes use Quick Response (QR) matrix barcodes to track and recover boxes. Clients use a phone app to scan the boxes after use and drop them off at convenient locations. The boxes are sanitized and reused, until they fail, at which point, they are recycled.

GOBoxes illustrate the potential benefits of shifting design goals from a focus on materials to a focus on the whole product system, and from single-use disposable products to more durable, reusable products. If the entrepreneurs had focused only on optimizing plastic materials for low hazard constituents or minimizing impacts from different waste and non-waste (recycling) pathways, they may have overlooked the potential for more sustainable solutions through disruptive innovation. Disruptive innovation results in new materials and products that provide the same function but in a different, and potentially much improved, way. Whole product assessment using life cycle thinking and supported by design principles and LCA, help identify opportunities for improvement and innovation. The same tools can also be used to confirm sustainability benefits.

7.3. Example Criteria

The design team should identify the most significant impacts, or ‘hot spots’, for the overall product system by benchmarking against the sustainable product design principles. Products with the fewest negative impacts across the whole product life cycle have sustainability benefits. But the tradeoffs will need to be evaluated further.

7.4. Challenges and Tradeoffs

Results from whole product system assessment help the design team identify data needs and opportunities for optimization. Comparing materials from the whole product perspective is particularly useful when assessing very different materials, product types and business models. However, overall benefits should not be used to justify unacceptable tradeoffs at any one life cycle stage. For example, a reduced carbon footprint does not justify the use of highly toxic additives.

8. Evaluation and Optimization

8.1. Goals

To encourage transparency, avoid unacceptable tradeoffs, ensure consideration of all of the sustainable design principles, and drive continual improvement.

8.2. Considerations

The knowledge gained by evaluating the whole product and impacts at each life cycle stage helps design teams select plastic materials and create plastic products that optimize for the sustainable design principles. Analysis shows where different materials or product design choices provide the greatest overall benefits and where additional information or data may be needed.

Impacts from individual life cycle stages and at the overall product level are interconnected. Optimizing certain chemicals or materials may change impacts at one or more life cycle stages and potentially for the overall system. For example, engineering students at Gonzaga University evaluated four polymeric food clamshell containers against sustainable design principles. Their analysis showed even small amounts of a toxic and persistent chemical additive greatly impacts the product's sustainability attributes. The additive created potential risks to workers, users, and the environment via waste and non-waste pathways. If the product did not contain a toxic additive, it would have scored much better overall than the other materials.[74]

Product design as a creative endeavor requires tradeoffs. While tradeoffs are inevitable and challenging, they can be managed in different ways.

Wherever there are tradeoffs, transparency supports credibility and ensures decisions are understandable. ‘Black box’ tools are not recommended because of lack of clarity on whether results align with stated sustainable design goals. Transparency also includes identifying data gaps and helps to prioritize which data gaps to fill. Design teams should document results and decisions based on their evaluation.

While tradeoffs are necessary, not all tradeoffs are acceptable. Design teams should establish early any key sustainable design goals and constraints and how they will be incorporated into the design and decision making process. Health and safety is prioritized at all life cycle stages and at the whole product level. Tradeoffs arise both between and within categories. For example, within chemical hazard assessment, different additives may have a range of different moderate hazards to humans or the environment. Tradeoffs between categories may also need to be made such as opting for a material made from virgin petroleum-based plastics in order to design a product for a closed-loop circularity program. Benchmarking these tradeoffs against product design goals and setting baseline limits for acceptable tradeoffs can help to ensure that the product design incorporates all of the sustainable plastic product design principles and does not overly compromise on one.

8.3. Example Criteria

Products can be compared based on how well they meet the sustainable product design goals at each life cycle stage and for the whole product system. Human health and safety should be prioritized. Documentation should accompany evaluation results and subsequent decisions.

The design team should use sensitivity analysis to identify which aspects of the plastic product are driving the most significant impacts. This may inspire ideas to improve sustainability performance. Products may also be compared based on opportunities for optimization.

8.4. Challenges and Tradeoffs

Addressing the many considerations and criteria presented in this report is challenging. Users would benefit from decision support tools, detailed guidance and metrics that support implementation. At the same time, product design is a creative endeavor and it is important that the considerations stimulate creativity, and allow for flexibility. Tools and metrics by nature can be prescriptive, leading to sub-optimal results.

Filling data gaps is time and resource intensive. All considerations identified in this report are subject to data gaps and subsequent uncertainty. Design teams need to use discretion in how they allocate resources. Focusing on those life cycle stages where humans and the environment are exposed to toxic chemicals should be prioritized. An iterative approach to filling data gaps can be used. Informed and principle-based decisions can be made without perfect information.

9. Conclusions and Recommended Next Steps

This report proposes a holistic, principle-based set of considerations and criteria for sustainable plastics from the chemicals perspective that are practical, meaningful and actionable. If the level of effort required is too high, they won't be used. Reasonable consensus on these considerations and criteria will lead to better understanding of how to apply existing tools and metrics and where additional efforts are needed. There was general agreement from the May 2018 OECD Global Forum on Environment – Plastics in a Circular Economy – Design of Sustainable Plastics from a Chemicals Perspective (Global Forum) that collectively, we must not delay. We need to act now and to continue to learn and progress.

Participants at the Global Forum identified a number of areas where more work is needed. Some of this work is appropriate for OECD and some may be better suited for governments, private sector businesses, university researchers, NGOs, etc. A summary of recommended areas for further development follows.

Expanding the scope of sustainability considerations. This report did not address all elements of sustainable product design such engineering performance specifications, regulatory requirements, social impact assessment or consideration of cost and availability. Future work could include these additional elements while remaining cognizant of current design realities. Criteria for choosing between plastic and non-plastic materials were also not considered. The choice of a material is a crucial first design choice, and the most sustainable choice may not be plastic.

Address global products and geographic differences. In the global economy, plastic products are produced and used all over the world. However, different geographic regions have different waste management situations. More work is needed to understand how to deal with variations in waste management infrastructure, waste regulations and policies, and culture. Should the product designer design plastic products based on the worst-case waste management infrastructure? How might products be designed for end of use in different markets? The issues of litter, particularly marine litter, and plastic recyclability are frequently mixed. But they should be treated separately. Preventing litter is more closely tied to whether a region has a viable waste management infrastructure. How to best recycle plastic products is an important question for innovation.

Use of plastics in short-lived versus long-lived products. More work is needed to understand how considerations and criteria for sustainable plastics relate to the intended longevity and durability of different plastic materials and plastic products. It is unclear if the considerations and criteria should be applied differently for plastics in long-lived versus short-lived goods, especially where reuse is not a viable option. Case studies are recommended.

Information on the quality, composition and recyclability of plastics. Recycled plastic feedstock use depends in part on the availability of recycled plastic of known and appropriate quality. An effective system is needed to define the purity of recycled plastics, including grades, and to facilitate communication in the supply chain. Databases and tools, such as product passports, are needed to provide information on constituents in recycled plastics. Each country should not set up different databases. The Global Automotive Declarable Substance List provides a good model for supply chain information that could be adopted for plastic products and constituents. A global RSL or MRSL of plastics substances could support quality and consistency in recycling. It would also be useful to have a summary of global regulations specific to constituents in plastics and plastic products. Tools and data that estimate how long is it efficient to keep a plastic cycling in the marketplace are also needed. Can plastics be fully circular? Relatively circular?

Next steps for implementing these considerations and criteria. Considerations and criteria developed in this report should be used to generate case studies by applying them to examples of different material and product types including short- and long-lived products. The considerations, criteria and examples should also be adapted for different target audiences such as policymakers, procurement specialists, etc.

A number of participants questioned the amount of time and resources needed to use the considerations and criteria to assess plastic products. While it is recommended to assess products in a tiered and iterative way, it is difficult to predict how much time and money is needed to inform decision making, especially given the diversity of plastics and products. Case studies would provide opportunities to gain such insight.

The primary audience for this report is designers; however, engaging with designers is a challenge. Participants recommended presenting this work at conferences and design forums and noted that designers don’t always have full design control. Brand owners need to be engaged as well. To be successful, a dialogue is needed across the value chain, and close collaboration is essential to transition to a circular economy. It was also recommended to bring this chemicals focused work to higher education.

Implementation. In the spirit of moving forward, participants raised questions about how to implement the considerations and criteria presented in this report and to make them operational. An integrated, multi-disciplinary approach is needed. Additional efforts to evolve this report and the other background documents into a guidance document are recommended. Task forces or small working groups could start the process. Transparency is an important component and examples are needed for how to describe trade-offs and for how best to document assessment work. Development of tools and approaches are needed that support optimisation between (conflicting) design goals, and provide guidance on how to approach data limitations, or to make choices when there are too many data.

Tools and definitions. OECD could help with the identification, development, and improvement of tools for assessing the toxicity of plastic materials. What are the best test methods and how should results be interpreted? Understanding the strengths and limitations of programs such as the USEPA Design for the Environment Polymer and GHS criteria would support this work. OECD could also help define sustainable criteria terminology (e.g. different types of biodegradability, waste paths, etc.) and develop hierarchies to guide development of sustainable plastics.

Appendix 1. Life Cycle Assessment

Life cycle assessment (LCA) is a standardized methodology (ISO 14040 series) for accounting for aspects and impacts tied to material and energy inputs and emissions associated with a product, process or service.[75] LCA methodology is typically used in a comparative way. Results vary depending on how the system boundaries are defined. 'Hot spots' or areas of greatest impact are identified and targeted for improvement opportunities. An LCA includes:

- Establishing the assessment goal and scope.
- Compiling an inventory of relevant energy and material inputs and environmental releases for all life cycle phases evaluated.
- Evaluating the potential environmental and human health impacts associated with identified inputs and releases from processes within phases evaluated.
- Interpreting the results to make an informed decision.

LCA provides a comprehensive picture of the impacts a chemical, product or process has on aspects of human health and the environment and helps manage tradeoffs. It is also an important tool used to check assumptions. Given the scope and depth of a standard LCA, the biggest challenge is data availability and understanding important system inputs. This can be especially challenging when manufacturing processes and chemical ingredients are held as proprietary information. The CalEPA Alternatives Analysis Guide provides an extensive list of LCA tools in its Appendix 7-2 including the following leading examples:

- EIO-LCA[76]: Estimates the materials and energy resources required for and the environmental emissions resulting from activities in our economy.
- GaBi[77]: Life cycle assessment software.
- SimaPro[78]: Life cycle assessment software.
- Plastics Europe Eco-profiles : Life cycle inventory information on many polymers. Data is based on direct measurements from the leading producers of the polymers.

Like all methodologies LCA is limited by available data. Conventional plastics are typically accounted for in well established and standardized LCA databases and software tools. However, newer materials or plastics manufactured in non-conventional ways may need customized data. Standard software packages consider multiple impact categories. In addition, high levels of uncertainty are associated with results and it can be challenging to know if differences are significant or within margins of error.

Given the potential scope of LCA it can be challenging to use LCA in a limited and pragmatic way. One strategy limits the scope of the system boundary. Another is to limit the number of aspects and impacts to evaluate. LCT as described in the report can be used to determine whether impacts associated with a given product are likely to be greater, lesser, or similar to those associated with other alternatives.

Appendix 2. Decision Methodologies

Sequential Method. In the Sequential Methodology, decisions are made at each evaluation point and only those alternatives that meet or exceed the criteria at any point continue on for further evaluation. The best analogy is a sieve where at each point along the process, data collected are used to differentiate between acceptable alternatives and those that do not have desired characteristics. At each point, data are collected only on those alternatives that pass through the prior sieve and the reasons for eliminating plastic options are documented. Documentation along the way is important. It enables others to understand the process but also could be needed if at the end of the assessment no viable alternatives are identified. The product developer may choose to revisit and alter decisions along the way in order to identify a viable option.

The Sequential Methodology is cost effective. Data gathering is costly with respect to time, expertise and money. At each step in the Sequential Methodology, the number of viable alternatives decreases, restricting data collection needs to only those that meet or exceed criteria and eliminating the need for further data collection on alternatives that have been screened out. The Sequential Methodology also has the benefit of facilitating a final recommendation more quickly than the other decision methodologies. For these reasons, it is a commonly used technique in the alternatives assessment process.

One negative aspect of the Sequential Methodology has limited its use by some organizations. At the end of the process, the alternatives identified may not include the optimal alternative(s) when one considers all the data simultaneously. As with most decisions, there are often tradeoffs between criteria. In the Sequential Methodology, an alternative may be eliminated early on based on one category, but it may be a preferred alternative based on the full set of criteria.

Simultaneous Methodology. In the Simultaneous Methodology, data are collected on all alternatives for all relevant categories and criteria. The product developer then creates a framework and a weighting scheme and documents the decision criteria. Using collected data, all alternatives are simultaneously compared against the desired criteria. When more than one material is found to be viable, additional criteria may be applied to further refine the preferred alternatives.

The benefit of the Simultaneous Methodology is that it retains more options throughout the decision-making process. The Simultaneous Methodology identifies materials with the lowest overall impact to human health and the environment. However, while optimized for an overall score, a material may be sub-optimal for any one category.

The negative side of the Simultaneous Methodology is that it is expensive and labor intensive because data are collected on all possible alternatives. In addition, the product developer must create ranking criteria against which all the alternatives are compared. Data gaps may become more of an issue because more data are needed. For these reasons, some organizations opt not to use the Simultaneous Methodology.

Hybrid Methodology. The Hybrid Methodology, as its name indicates, is a mixture of the Sequential and Simultaneous Methodologies. In the Hybrid Methodology, the Sequential

Method is used for a few criteria and the alternatives that remain at the end of that process are subjected to a complete evaluation using the Simultaneous Methodology. For example, an organization may decide to use the Sequential Method for the performance and toxicity evaluations. Only those plastics that meet or exceed the performance requirements are submitted for a toxicity evaluation. Upon completion of the toxicity evaluation, only those polymers that meet or exceed performance and toxicity requirements are evaluated using the Simultaneous Methodology for the remaining decision criteria.

The Hybrid Methodology has the benefit of addressing to a degree the pros and cons identified for the Sequential and Simultaneous methodologies. By using the Sequential Methodology, cost and resource requirements are reduced by concentrating limited resources on the most viable candidates. By using the Simultaneous Methodology, evaluation is conducted on a broader pool of alternatives.

Because of its flexibility and its optimized use of resources, the Hybrid Methodology may be the preferred approach for evaluating alternatives.

Appendix 3. Hazard Endpoints Typically Used in Full Chemical Hazard Assessment

A List of Typical Hazard Endpoints for Chemical Hazard Assessment
Human Health Effects
Carcinogenicity
Genotoxicity/Mutagenicity
Reproductive toxicity
Developmental toxicity (explicitly includes neurodevelopmental toxicity)
Endocrine Activity (Disruption)
Acute Mammalian toxicity
Specific Target Organ Toxicity (Systemic toxicity) – single dose
Specific Target Organ Toxicity (Systemic toxicity) – repeated dose
Neurotoxicity
Skin Sensitization
Respiratory Sensitization
Eye Irritation/Corrosion
Dermal Irritation/Corrosion
Ecotoxicity
Acute Aquatic Toxicity
Chronic Aquatic Toxicity
Environmental Fate and Transport
Persistence
Bioaccumulation
Physical Hazards
Flammability (liquids, solids, etc.)
Explosivity and Reactivity (self-reactive, pyrophoric, etc.)
Additional Endpoints
Ecotoxicity: avian (acute oral and dietary) and acute bee toxicity; Terrestrial toxicity (earthworm)

Appendix 4. Example USEPA Design for the Environment CHA Table

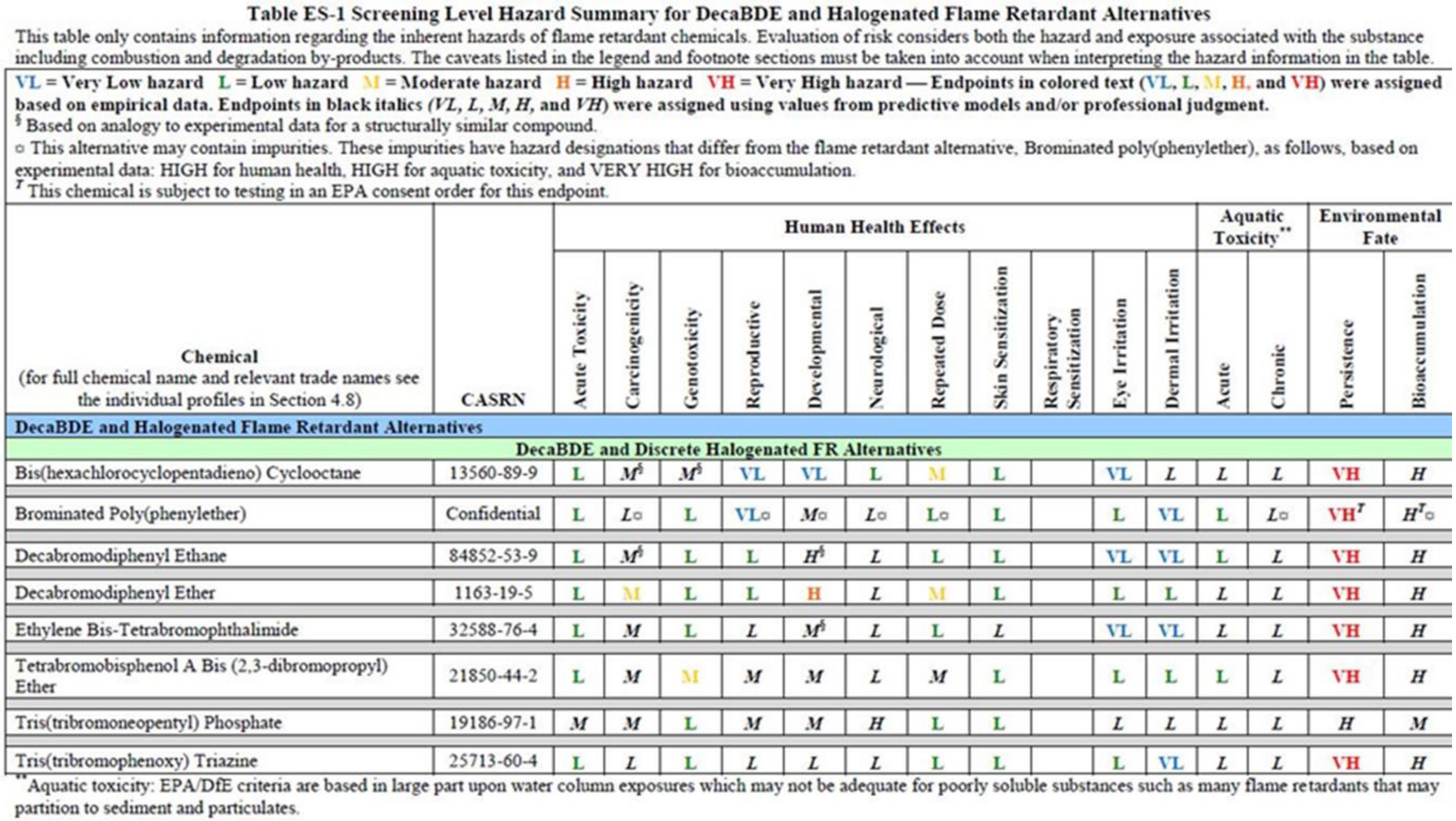


Table ES-1 Screening Level Hazard Summary for DecaBDE and Halogenated Flame Retardant Alternatives

This table only contains information regarding the inherent hazards of flame retardant chemicals. Evaluation of risk considers both the hazard and exposure associated with the substance including combustion and degradation by-products. The caveats listed in the legend and footnote sections must be taken into account when interpreting the hazard information in the table.

VL = Very Low hazard L = Low hazard M = Moderate hazard H = High hazard VH = Very High hazard — Endpoints in colored text (VL, L, M, H, and VH) were assigned based on empirical data. Endpoints in black italics (*VL, L, M, H,* and *VH*) were assigned using values from predictive models and/or professional judgment.

[§] Based on analogy to experimental data for a structurally similar compound.

○ This alternative may contain impurities. These impurities have hazard designations that differ from the flame retardant alternative, Brominated poly(phenylether), as follows, based on experimental data: HIGH for human health, HIGH for aquatic toxicity, and VERY HIGH for bioaccumulation.

[T] This chemical is subject to testing in an EPA consent order for this endpoint.

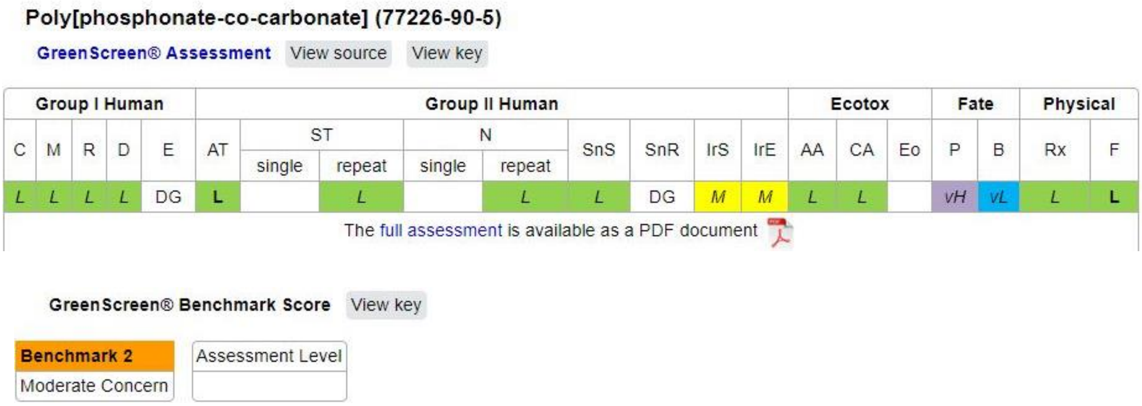
Chemical (for full chemical name and relevant trade names see the individual profiles in Section 4.8)	CASRN	Human Health Effects											Aquatic Toxicity[**]		Environmental Fate	
		Acute Toxicity	Carcinogenicity	Genotoxicity	Reproductive	Developmental	Neurological	Repeated Dose	Skin Sensitization	Respiratory Sensitization	Eye Irritation	Dermal Irritation	Acute	Chronic	Persistence	Bioaccumulation
DecaBDE and Halogenated Flame Retardant Alternatives																
DecaBDE and Discrete Halogenated FR Alternatives																
Bis(hexachlorocyclopentadieno) Cyclooctane	13560-89-9	L	*M*[§]	*M*[§]	VL	VL	L	M	L		VL	*L*	*L*	*L*	VH	*H*
Brominated Poly(phenylether)	Confidential	L	*L*○	L	VL○	*M*○	*L*○	L○	L		L	VL	L	*L*○	VH[T]	*H*[T]○
Decabromodiphenyl Ethane	84852-53-9	L	*M*[§]	L	L	*H*[§]	*L*	L	L		VL	VL	L	*L*	VH	*H*
Decabromodiphenyl Ether	1163-19-5	L	M	L	L	H	*L*	M	L		L	L	*L*	*L*	VH	*H*
Ethylene Bis-Tetrabromophthalimide	32588-76-4	L	*M*	L	*L*	*M*[§]	*L*	L	*L*		VL	VL	*L*	*L*	VH	*H*
Tetrabromobisphenol A Bis (2,3-dibromopropyl) Ether	21850-44-2	L	*M*	M	*M*	*M*	*L*	*M*	L		L	L	L	*L*	VH	*H*
Tris(tribromoneopentyl) Phosphate	19186-97-1	*M*	*M*	L	*M*	*M*	*H*	L	L		*L*	*L*	*L*	*L*	*H*	*M*
Tris(tribromophenoxy) Triazine	25713-60-4	L	*L*	L	*L*	*L*	*L*	L	L		L	VL	*L*	*L*	VH	*H*

[**] Aquatic toxicity: EPA/DfE criteria are based in large part upon water column exposures which may not be adequate for poorly soluble substances such as many flame retardants that may partition to sediment and particulates.

Appendix 5. An Example GreenScreen Hazard Table with Benchmark Score

Benchmark Chemicals

In addition to summarizing hazard classifications by endpoint, GS also provides an overall chemical benchmark score ranging from Benchmark 1 (Chemical of High Concern) to Benchmark 4 (Safer Chemical). The GS Benchmarks align with global governmental regulatory priorities linking hazard endpoints and combination of endpoints to criteria for substances of very high concern as defined in the European Union's REACH legislation and in the Canadian Domestics Substances List screening program. The full report associated with the summary hazard table below is freely and publicly available from the Interstate Chemicals Clearinghouse chemical hazard assessment database. [79]



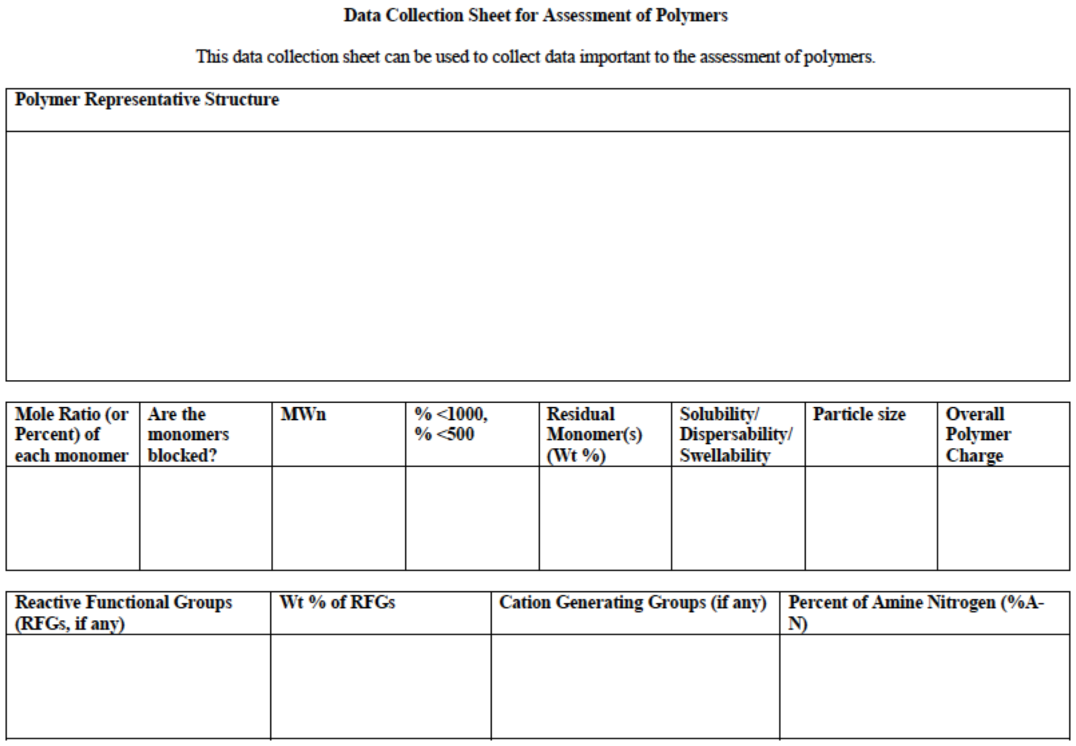
Poly[phosphonate-co-carbonate] (77226-90-5)

Group I Human					Group II Human									Ecotox			Fate		Physical	
C	M	R	D	E	AT	ST		N		SnS	SnR	IrS	IrE	AA	CA	Eo	P	B	Rx	F
						single	repeat	single	repeat											
L	*L*	*L*	*L*	DG	**L**		*L*		*L*	*L*	DG	*M*	*M*	*L*	*L*		*vH*	*vL*	*L*	**L**

The full assessment is available as a PDF document

Benchmark 2	Assessment Level
Moderate Concern	

Appendix 6. Data Collection Template for Assessment of Polymers[80]



Data Collection Sheet for Assessment of Polymers

This data collection sheet can be used to collect data important to the assessment of polymers.

Polymer Representative Structure

Mole Ratio (or Percent) of each monomer	**Are the monomers blocked?**	**MWn**	**% <1000, % <500**	**Residual Monomer(s) (Wt %)**	**Solubility/ Dispersability/ Swellability**	**Particle size**	**Overall Polymer Charge**

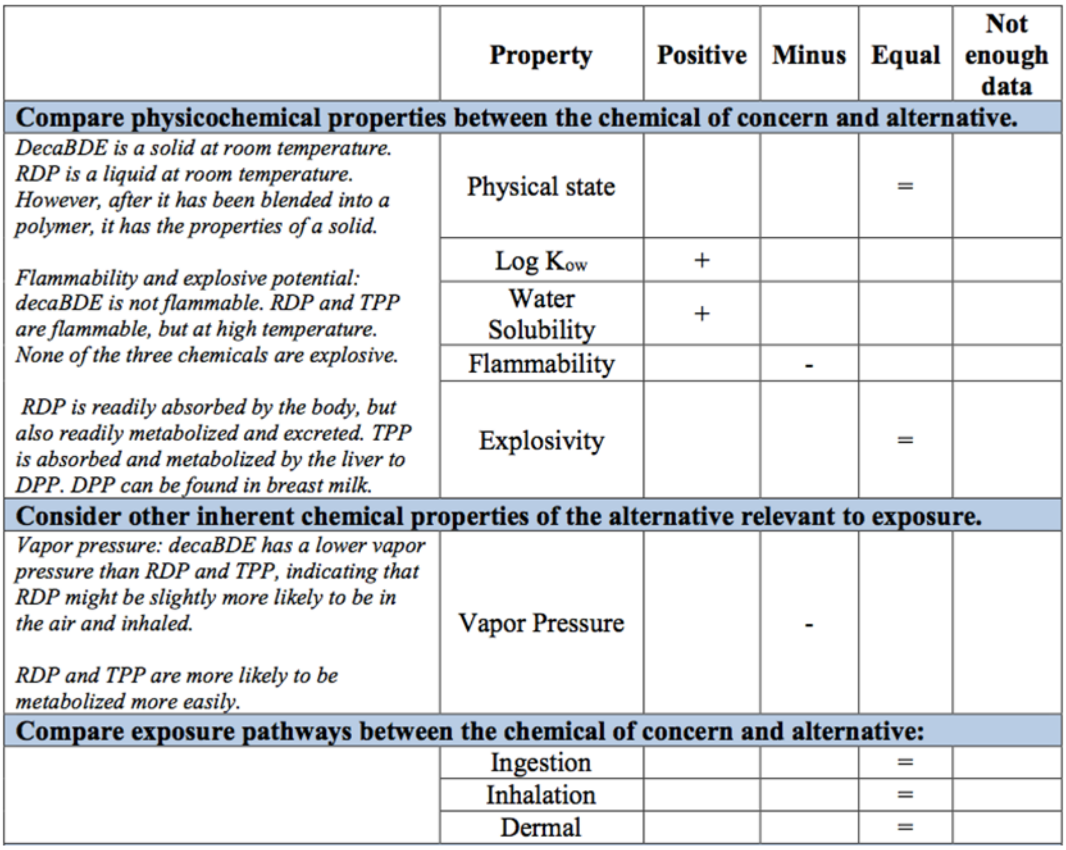
Reactive Functional Groups (RFGs, if any)	**Wt % of RFGs**	**Cation Generating Groups (if any)**	**Percent of Amine Nitrogen (%A-N)**

* From USEPA Interpretive Assistance Document for Assessment of Polymers.

Appendix 7. Example Approach for Comparative Exposure Assessment[81]

Comparison Criteria. A useful way to compare exposure for substances in plastic materials is to set up a comparative exposure table. The following illustrates how two possible flame retardants in a plastic might be compared (+, - or =) for a limited set of chemical and product exposure parameters.

Comparing example inherent properties of additives for exposure



	Property	**Positive**	**Minus**	**Equal**	**Not enough data**
Compare physicochemical properties between the chemical of concern and alternative.					
DecaBDE is a solid at room temperature. RDP is a liquid at room temperature. However, after it has been blended into a polymer, it has the properties of a solid. *Flammability and explosive potential: decaBDE is not flammable. RDP and TPP are flammable, but at high temperature. None of the three chemicals are explosive.* *RDP is readily absorbed by the body, but also readily metabolized and excreted. TPP is absorbed and metabolized by the liver to DPP. DPP can be found in breast milk.*	Physical state			=	
	Log K_{ow}	+			
	Water Solubility	+			
	Flammability		-		
	Explosivity			=	
Consider other inherent chemical properties of the alternative relevant to exposure.					
Vapor pressure: decaBDE has a lower vapor pressure than RDP and TPP, indicating that RDP might be slightly more likely to be in the air and inhaled. *RDP and TPP are more likely to be metabolized more easily.*	Vapor Pressure		-		
Compare exposure pathways between the chemical of concern and alternative:					
	Ingestion			=	
	Inhalation			=	
	Dermal			=	

Appendix 8. Example Exposure Map (Greggs et al.)

Life Cycle Stage	Action to Use Product	Expected Receiving Medium	Release Mechanism & Fate and Transport During/After Use	Potential Exposure Medium	Exposure Route	Receptors							
						Terrestrial			Wetland/ Riperian	Aquatic			WWTP
						Vertebrates	Invertebrates	Plants	Plants	Vertebrates	Invertebrates	Plants	Micro-organisms
🟦 Use of Eau de Toilette	🟦 Sprayed	Ambient Air	🟦 Volatilization	🟦 Ambient Air (including soil pore air)	Inhalation or Respiration	⬜	⬜	⬜	⬜	⬛	⬛	⬛	⬛
	Applied with Tool	🟦 Skin Surface - Human or Pets	🟦 Aerosolization	Upland Soil (including pore water)	Direct Contact	⬜	⬜	⬛	⬛	⬛	⬛	⬛	⬛
	🟦 Applied with Hand	Indoor Surfaces	🟦 Evaporation		Ingestion/Root Uptake	⬜	⬜	⬜	⬛	⬛	⬛	⬛	⬛
	Contacted	Indoor Dust	Migration	Wetland/Riparian Soil (including pore water)	Direct Contact	⬜	⬜	⬛	⬛	⬛	⬛	⬛	⬛
	Poured Liquids	Outdoor Surfaces	🟦 Re-suspension		Ingestion/Root Uptake	⬜	⬜	⬛	⬜	⬛	⬛	⬛	⬛
	Poured Solids	Food and/or Drink	Dissolving		Incidental Ingestion	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
	Evaporated Liquids or Solids	Drain Water	Contacting	🟦 WWTP Sludge	🟦 Direct Contact	🟦	🟦	🟦	⬛	⬛	⬛	⬛	🟦
	Mouthed	Surface Water	🟦 Washing		🟦 Ingestion/Gill Uptake	🟦	🟦	⬛	⬛	🟦	🟦	⬛	🟦
	Swallowed	Sediment	🟦 Waste Water Treatment	🟦 Surface Water	🟦 Direct Contact	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬛
		Soil	Leaching		🟦 Ingestion/Root Update/Gill Uptake	🟦	🟦	🟦	🟦	🟦	🟦	🟦	⬛
		Animals	Erosion/Runoff	🟦 Sediment	🟦 Direct Contact	🟦	⬛	⬛	🟦	🟦	🟦	⬛	⬛
		Plants	Animal Uptake		🟦 Ingestion/Gill Uptake	🟦	⬛	⬛	⬛	🟦	🟦	⬛	⬛
		Human Digestive Tract	Plant Uptake	🟦 Ground Water	🟦 Ingestion/Root Uptake	🟦	🟦	🟦	🟦	⬛	⬛	⬛	⬛
			Incineration	Diet	Ingestion	⬜	⬜	⬛	⬛	⬜	⬜	⬛	⬛
			Landfilling										

Key	
🟦	Relevant to Use
⬜	Not Relevant to Use
⬛	Not Applicable

References

[1] https://www.ellenmacarthurfoundation.org/circular-economy

[2] American Chemical Society (ACS) Green Chemistry Institute (GCI), 2015. Design Principles for Sustainable Green Chemistry & Engineering,

www.acs.org/content/dam/acsorg/greenchemistry/resources/2015-gci-design-principles.pdf.

[3] Hermabessiere, et al. (2017). Occurrence and effects of plastic additives on marine environments and organisms: A review. *Chemosphere*. 182. 781-793.

[4] American Chemical Society (ACS) Green Chemistry Institute (GCI), 2015. Design Principles for

Sustainable Green Chemistry & Engineering,

www.acs.org/content/dam/acsorg/greenchemistry/resources/2015-gci-design-principles.pdf.

[5] Organization for Economic Cooperation and Development (OECD), 2010. OECD Global Forum on Environment Focusing on Sustainable Materials Management, OECD Environment Directorate, 2010, 55 pages, http://www.oecd.org/env/waste/111789.pdf.

[6] United Nations General Assembly (March 20, 1987). "Report of the World Commission on Environment and Development: Our Common Future; Transmitted to the General Assembly as an Annex to document A/42/427 – Development and International Co-operation: Environment; Our Common Future, Chapter 2: Towards Sustainable Development; Paragraph 1". United Nations General Assembly, http://www.un-documents.net/our-common-future.pdf, Retrieved April 2018.

[7] United Nations General Assembly (2005). 2005 World Summit Outcome, Resolution A/60/1, adopted by the General Assembly on 16 September 2005, http://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_60_1.pdf, retrieved on April 2018.

[8] Lemonick, Sam. June 18, 2018. Chemical solutions for a chemical problem. Chemical and Engineering News.

[9] Ellen MacArthur Foundation, 2017, New Plastics Economy Initiative, https://newplasticseconomy.org/, accessed 2/2018.

[10] https://www.goboxpdx.com

[11] Organisation for Economic Cooperation and Development (OECD), May 24, 2018. Infographic. Improving Markets for Recycled Plastics. https://www.oecd.org/environment/improving-markets-for-recycled-plastics-9789264301016-en.htm

[12] California Environmental Protection Agency (CalEPA), 2017. Department of Toxic Substances Control, *Safer Consumer Products Alternatives Analysis Guide*, Version 1.0, June 2017, 235 pages.

[13] Interstate Chemicals Clearinghouse (IC2), 2017. *Interstate Chemicals Clearinghouse Alternatives*

Assessment Guide, Version 1.1 http://theic2.org/article/download-

pdf/file_name/IC2_AA_Guide_Version_1.1.pdf, 183 pages.

[14] World Forum on Natural Capital. https://naturalcapitalforum.com. Accessed March 2018

[15] https://product-social-impact-assessment.com/wp-content/uploads/2014/07/Handbook-for-Product-Social-Impact-Assessment-3.0.pdf

[16] Natural Capital Protocol Toolkit. https://www.naturalcapitaltoolkit.org. Accessed. April 2018

[17] Plastic Recyclers Europe, 2018. RecyClass software, www.plasticsrecyclers.eu/recyclass, accessed 2018.

[18] Devaney, L, M. Henchion and A. Regan. 2017. Good goverance in the bioeconomy. Agricultural Economics Society and European Association of Agricultural Economists. DOI: 10.1111/1746-692X.12141

[19] Lithner, Delilah. 2011. Environmental and Health Hazards of Chemicals in Plastic Polymers and Products. Ph.D. thesis. Dept. of Plant and Environmental Sciences. University of Gothenberg.

[20] https://www.epa.gov/sites/production/files/2015-03/documents/osha_carcinogen_basis_march_2015_0.pdf

[21] EPA, 2011. *Design for the Environment Program Alternatives Assessment Criteria for Hazard Evaluation*, Version 2.0, August 2011, https://www.epa.gov/sites/production/files/2014-01/documents/aa_criteria_v2.pdf.

[22] Organisation for Economic Cooperation and Development (OECD), 2015a. OECD Substitution and Alternatives Assessment Tool Selector www.oecdsaatoolbox.org/Home/Tools.

[23] California Environmental Protection Agency (CalEPA), 2017. Department of Toxic Substances Control, *Safer Consumer Products Alternatives Analysis Guide*, Version 1.0, June 2017, 235 pages.

[24] Presented by Peter Saling at the OECD Global Forum on Environment – Plastics in a Circular Economy. https://www.slideshare.net/secret/8rcYoHp9hocgtt Accessed July 2018

[25] https://wwwn.cdc.gov/Niosh-oeb/Home/Index

[26] http://www.hse.gov.uk/coshh/essentials/index.htm

[27] https://www.gadsl.org

[28] IC2, 2015. Chemical Hazard Assessment Database, http://www.theic2.org/hazard-assessment, accessed 2/2018.

[29] Organisation for Economic Cooperation and Development (OECD), 2015a. OECD Substitution and Alternatives Assessment Tool Selector http://www.oecdsaatoolbox.org/Home/Tools.

[30] California Environmental Protection Agency (CalEPA), 2017. Department of Toxic Substances Control, *Safer Consumer Products Alternatives Analysis Guide*, Version 1.0, June 2017, 235 pages.

[31] EPA, 207. Toxicology Testing in the 21st Century (Tox21), https://www.epa.gov/chemical-research/toxicology-testing-21st-century-tox21, accessed 2/010.

[32] United Nations (UN), 2015. Globally Harmonized System of Classification and Labelling of Chemicals (GHS), Sixth revised edition, ST/SG/AC.10/30/Rev.6, 527 pages.

[33] EPA, 2011. *Design for the Environment Program Alternatives Assessment Criteria for Hazard Evaluation*, Version 2.0, August 2011, https://www.epa.gov/sites/production/files/2014\01/documents/aa_criteria_v2.pdf.

[34] Clean Production Action (CPA), 2017. GreenScreen for Safer Chemicals, Version 1.4, https://www.greenscreenchemicals.org/.

[35] MBDC, 2012. Material Health Assessment Methodology, Cradle to Cradle Certified^{CM} Product Standard, Version 3.0, 92 pages, http://www.c2ccertified.org/images/uploads/C2CCertified_Material_Health_Methodology_121112.pdf.

[36] California Environmental Protection Agency, Office of Environmental Health and Human Assessment (OEHHA), 2012. Green Chemistry Hazard Traits for California's Toxics information Clearinghouse, 29 pages, https://oehha.ca.gov/media/downloads/risk-assessment//gcregtext011912.pdf, accessed 2/2018.

[37] Clean Production Action (CPA), 2017. GreenScreen for Safer Chemicals v 1.4 https://www.greenscreenchemicals.org/.

[38] EPA DFE, 2014. An Alternatives Assessment for the Flame Retardant Decabromodiphenyl Ether (DecaBDE), January 2014, 901 pages, accessed 3/2018, https://www.epa.gov/sites/production/files/2014-05/documents/decabde_final.pdf.

[39] Washington Department of Ecology (Ecology), 2014. *Quick Chemical Assessment Tool*, June 2016, 125 pages, https://fortress.wa.gov/ecy/publications/SummaryPages/1404033.html.

[40] Healthy Building Network (HBN), 2017. Pharos Chemical and Material Library, https://www.pharosproject.net/, accessed 2/2018.

[41] https://commons.healthymaterials.net/login

[42] http://chemsec.org/business-tool/sin-list

[43] European Commission (EC), 2015. Technical Assistance Related to the Review of REACH with Regard to the Registration Requirements on Polymer: Final Report, written by BIO by Deloitte, 235 pages.

[44] Groh, K.J. et al .2017. Food contact materials and gut health: Implications for toxicity assessment and relevance of high molecular weight migrants. Food Chem. Toxicol., Nov;109(Pt 1):1-18.

[45] European Commission (EC), 2015. Technical Assistance Related to the Review of REACH with Regard to the Registration Requirements on Polymer: Final Report, written by BIO by Deloitte, 235 pages.

[46] European Commission (EC), 2015. Technical Assistance Related to the Review of REACH with Regard to the Registration Requirements on Polymer: Final Report, written by BIO by Deloitte, 235 pages.

[47] Organization for Economic Cooperation and Development (OECD), 2010. OECD Global Forum on Environment Focusing on Sustainable Materials Management, OECD Environment Directorate, 2010, 55 pages, http://www.oecd.org/env/waste/111789.pdf.

[48] EPA, 2013. Interpretive Assistance Document for Assessment of Polymers: Sustainable Futures Summary Assessment, updated June 2013, 13 pages.

[49] Lithner, Delilah. 2011. Environmental and Health Hazards of Chemicals in Plastic Polymers and Produts. Ph.D. thesis. Dept. of Plant and Environmental Sciences. University of Gothenberg.

[50] REVIEW OF REACH WITH REGARD TO THE REGISTRATION REQUIREMENTS ON POLYMERS 070307/2011/602175/SER/D3. Final Report. Part A: Polymers. Annex 1: http://ec.europa.eu/environment/chemicals/reach/studies/study10_review_2012_en.htm

[51] OECD (2009): Data analysis of the identification of correlations between polymer characteristics and potential for health or ecotoxicological concern, ENV/JM/MONO(2009)1.

[52] McDonough Braungart Design Chemistry, 2012. Cradle to Cradle Certified Product Standard Version 3.0, 116 pages, http://www.c2ccertified.org/images/uploads/C2CCertified_Product_Standard_V3_121112.pdf.

[53] EPA, 2013. Interpretive Assistance Document for Assessment of Polymers: Sustainable Futures Summary Assessment, updated June 2013, 13 pages.

[54] Clean Production Action (CPA), 2017. GreenScreen for Safer Chemicals https://www.greenscreenchemicals.org/.

[55] Plastics Scorecard v1.0. 2014. https://www.bizngo.org/sustainable-materials/plastics-scorecard. Accessed 2018

[56] Why Apple Makes its Own Sweat, www.youtube.com/watch?v=8bLjD5ycBR0; accessed July 2018

[57] Groh, K.J, and J. Muncke. 2017. In vitro toxicity testing of food contact materials: State of the art and future challenges. Comprehensive reviews in Food Science and Food Safety. 14 July 2017.

[58] Review of REACH with regard to the registration requirements for polymers and 1 to 10 tonne substances. Prepared for European Commission DG Environment. December 2012. ec.europa.eu/environment/chemicals/reach/pdf/studies_review2012/annexe1_study10.pdf

[59] National Research Council of the National Academy of Sciences (NAS), 2014. *A Framework to Guide Selection of Chemical Alternatives*, Washington DC, The National Academies Press, 280 pages.

[60] Greggs, William, et al., 2018. Qualitative Approach to Comparative Exposure in Alternatives Assessments, pre-publication, Integrated Environmental Assessment and Management.

[61] Greggs, William, et al., 2018. Qualitative Approach to Comparative Exposure in Alternatives Assessments, pre-publication, Integrated Environmental Assessment and Management.

[62] Lithner, Delilah et al., 2011. Environmental and Health Hazard Ranking and Assessment of Plastic Polymers Based on Chemical Composition, Science of the Total Environment, 409, pp. 3309-3324.

[63] Stichting Vu, 2016. ENFIRO (Life cycle Assessment of Environment-compatible Flame Retardants (Prototypical case study), https://cordis.europa.eu/result/rcn/56829_en.html, accessed 2/2018.

[64] Greggs, William, et al., 2018. Qualitative Approach to Comparative Exposure in Alternatives Assessments, pre-publication, Integrated Environmental Assessment and Management.

[65] OECD, 2018. Improving Markets for Recycled Plastics. Trends, Prospects and Policy Responses. ISBN 9789264301016. https://doi.org/10.1787/9789264301016-en

[66] Ocean Recovery Alliance. 2015. 2015 Plastics-to-Fuel Project Developer's Guide. http://www.oceanrecov.org/assets/files/Valuing_Plastic/2015-PTF-Project-Developers-Guide.pdf

[67] European Commission DG ENV. Plastic Waste in the Environment. Revised Final Report. April 2011.

[68] Kreuder, A.V., House-Knight, T., Whitford, J. , Ponnusamy, E., Miller, P., Jesse, N., Rodenborn, R., Sayag, S., Gebel, M., Aped., Sharfstein., Manaster, E., Ergas, I., Harris, A., and Grice, L.N. 2017. A Method for Assessing Greener Alternatives between Chemical Products Following the 12 Principles of Green Chemistry. ACS Sustainable Chem. Egr. 5, 2927-2935.

[69] Plastic Recyclers Europe, 2018. RecyClass software, http://www.plasticsrecyclers.eu/recyclass, accessed 2018.

[70] Paktech. Paktech-opi.com. Accessed July 2018

[71] How2Recycle Program. http://greenblue.org/work/how2recycle/. Accessed March 2018

[72] She found a way to make plastic waste useful by Chandana Banerjee March 30, 2017 The Christian Science Monitor. https://www.csmonitor.com/World/Making-a-difference/2017/0330/She-found-a-way-to-make-plastic-waste-useful

[73] https://www.goboxpdx.com

[74] Converting Design Principles into Metrics using Alternatives Assessment: A Case Study on Food Clamshell Take-Out Containers. https://www.northwestgreenchemistry.org/publications/. Accessed July 2018

[75] International Organization for Standardization, 2006. 14040:2003, Environmental Management-Life cycle assessment-Principles and framework, 20 pages, https://www.iso.org/standard/37456.html.

[76] Carnegie Mellon University, 2014. Economic Input-Output Life cycle Assessment (EIO-LCA) Method, http://www.eiolca.net/, accessed 2/2018.

[77] Thinkstep GaBi, 2012. GaBi software, http://www.gabi-software.com/america/overview/product-sustainability-performance/, accessed 2/2018.

[78] Pre, 20017. SimaPro LCA software, https://simapro.com/, accessed 2/2018.

[79] IC2, 2015. Chemical Hazard Assessment Database, http://www.theic2.org/hazard-assessment, accessed 2/2018.

[80] USEPA Interpretive Assistance Document for Assessment of Polymers. Sustainable Futures Summary Assessment. Updated June 2013

[81] IC2, 2017. *Interstate Chemicals Clearinghouse Alternatives Assessment Guide*, Version 1.1 http://theic2.org/article/download-pdf/file_name/IC2_AA_Guide_Version_1.1.pdf, 183 pages.

OECD

Visit the Forum website

http://oe.cd/plastics-forum

For more information on OECD work on plastics

www.oecd.org/chemicalsafety
www.oecd.org/environment/waste

Contacts
Peter.Borkey@oecd.org (circular economy programme)
Eeva.Leinala@oecd.org (chemicals programme)

Engage with us on Twitter:

@OECD_ENV

This event was organised in collaboration with:

Ministry of Environment and Food of Denmark

This event was co-funded by:

Co-funded by the European Union

Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety

Nordic Council of Ministers

BUNDESMINISTERIUM FÜR NACHHALTIGKEIT UND TOURISMUS