CONSIDERATIONS AND CRITERIA FOR SUSTAINABLE PLASTICS FROM A CHEMICALS PERSPECTIVE

BACKGROUND PAPER 1

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Plastics in a Circular Economy
Designing sustainable plastics
from a chemicals perspective

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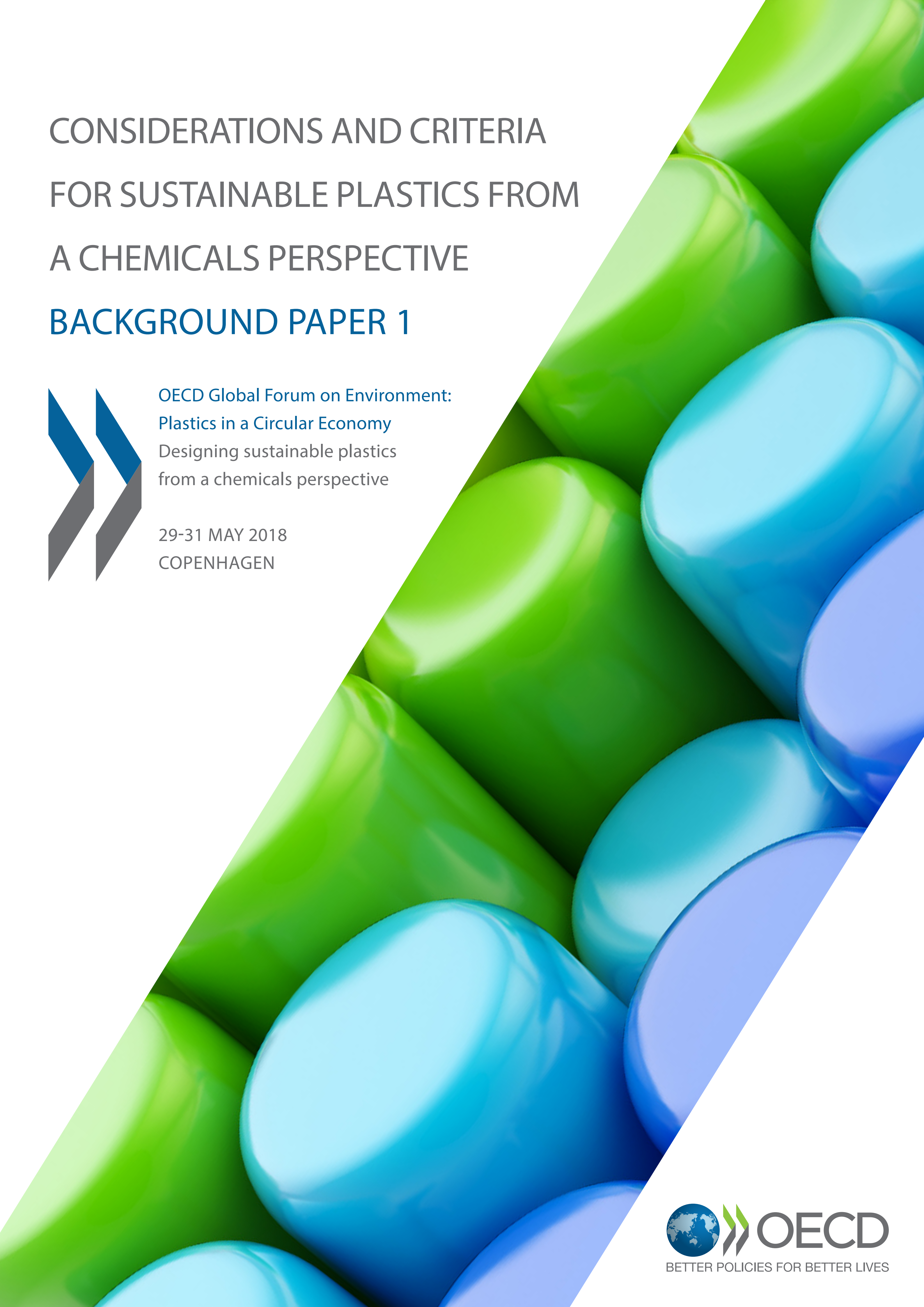

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Considerations and Criteria for Sustainable Plastics from a Chemicals Perspective

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EXECUTIVE SUMMARY

Sustainable plastics provide societal benefits while enhancing human and environmental health and safety across the entire product life cycle. By definition, sustainable plastics are managed within a sustainable materials management system (a Circular Economy)[1] to avoid the creation of waste, toxics and pollution. But even non-toxic 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 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.

Considerations and criteria identified in this report are linked to established principles and tools for sustainable materials management and sustainable product design. Using principles to guide development preserves flexibility and helps to avoid being constrained by what is currently measurable using 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 for measurement.

A number of useful tools already exist to measure various aspects of sustainability and to quantify how products fulfill the vision set forth by these design principles. Such tools include life cycle assessment (LCA), chemical inventory and disclosure, chemical hazard assessment (CHA), exposure assessment (EA), stakeholder assessment, alternatives assessment (AA) and others. Information on tools is provided or referenced throughout this report. However, each of these tools only evaluates only one or, at best, a few sustainability attributes. In addition, sustainability attributes can be heavily interrelated. Improvement in one area may result in undesirable changes in another. It is important to be aware of potential tradeoffs and to make informed decisions.

In 2010, the OECD established four Policy Principles for Sustainable Materials Management (SMM) as follows:[2]

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.

The American Chemical Society Green Chemistry Institute distilled Sustainable Design Principles from the Principles of Green Chemistry and Engineering:[3]

1. **Design systems holistically and use life cycle thinking.** This is a broad and overarching principle that applies to the design of all sustainable chemicals including plastics. A plastic is not sustainable inherently. Rather, 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 with the end in mind.'
2. **Maximize resource efficiency**. Resource efficiency is not just about being efficient and doing more with less. It also includes the imperative to preserve natural capital in alignment with the SMM Policy Principle 1. Resources that are renewable should not be used faster than they can be

regenerated. And 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.

3. **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 may be mistaken as food by wildlife when it leaks into the environment.

Sustainable product design is an iterative, circular process of continual improvement. But one has to start somewhere. The recommended first step is for the product designer to establish design goals using life cycle thinking including a plan for product disposal and recycling. From there, designers can gather information for considerations and criteria tied to feedstock selection, production and manufacturing, product use and disposal/recovery options. After assessing each independent life cycle stage, the designer is encouraged to take a holistic look at the product as a whole and to benchmark it against other products that provide the same desired service. At the end of the assessment is the opportunity for evaluation and optimization and for continual product improvement toward sustainable design principles. A holistic and principle-based approach to product design can help to drive both incremental improvements and disruptive innovations.

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1.0 INTRODUCTION

Sustainable plastics provide societal benefits while enhancing human and environmental health and safety across the entire product life cycle. They can also contribute to meeting the UN Sustainable Development Goals.[4, 5] By definition, sustainable plastics are managed within a sustainable materials management system to avoid the creation of waste, toxics and pollution. Even non-toxic plastics derived from non-toxic constituents are not sustainable plastics if they end up as litter and form microplastics in the oceans.[6] 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. In 2010, the OECD established four Policy Principles for Sustainable Materials Management (SMM):[7]

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 both product design and policy perspectives. Principles 3 and 4 are core to practices that drive the adoption of sustainable materials. These include the alignment of policy initiatives such as chemical restrictions, taxes and incentives, and procurement requirements. Voluntary initiatives that engage all parts of society to drive product stewardship and informed purchasing decisions are also important practices. Each of us plays a role in sustainable materials management through decisions about product design, development, procurement and waste management. However, manufacturers and product developers have the primary influence on the selection of polymer types and product design decisions.

Several organizations have defined similar aspirational product design principles, the American Chemical Society Green Chemistry Institute's Sustainable Design Principles that are derived from the Principles of Sustainable and Green Chemistry and Engineering are as follows:[8 9,10,11]

1. **Design systems holistically and use life cycle thinking.** This is a broad and overarching principle that applies to the design of all materials, including plastics. A plastic is not sustainable inherently. Rather, 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 with the end in mind.'
2. **Maximize resource efficiency**. Resource efficiency is not just about being efficient and doing more with less. It also includes the imperative to preserve natural capital in alignment with the SMM Policy Principle 1. Resources that are renewable should not be used faster than they can be regenerated. And 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.
3. **Eliminate and minimize hazards and pollution**. Risk is a function of hazard and exposure. Reducing the inherent hazards of chemicals can reduce 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.

Consensus on sustainable design principles is important because it allows for agreement on criteria that support realization of the principles. The criteria can then pave the way 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 life cycle assessment (LCA), chemical inventory and disclosure, chemical hazard assessment (CHA), exposure assessment (EA), stakeholder assessment, alternatives assessment (AA) and others. And more continue to be developed. Each of these tools evaluates only one, or at best, a few sustainability attributes. Because sustainability attributes are heavily interrelated, improvement in one area may result in undesirable changes in another. It is important to be aware of potential tradeoffs and to make informed decisions. This report is intended to help show how these tools can be used together to realize a vision for sustainable plastics.

Vision and principles should drive tool use and not the other way around. In the past, arguments have focused on how to trade off results from one tool against results from another (e.g. LCA versus risk assessment) without an integrated sustainability context. Focusing on just one attribute or even just one principle can result in perverse outcomes. A plastic, no matter how safe the ingredients used to make it, can still cause harm if it is not managed properly. Likewise, chemicals derived from rapidly renewable, biobased feedstock can be made into toxic substances. Therefore, one should not concentrate only on a single 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:

- **Design innovation.** E.g. Designing new products that meet performance requirements while integrating sustainable design principles and reducing the use and generation of toxic substances and waste.
- **Materials innovation**. E.g. Achieving performance requirements without the use of toxic additive or creating inherently biodegradable materials that fit within the existing materials management infrastructure. Use of renewable feedstock that:
  - Does not compete with food production (such as agricultural wastes grown and harvested in a sustainable way)
  - Uses minimal pesticides and fertilizers
  - Does not transform socially unused landscapes (like forests, savanna/steppe, grass- or marshlands) into agricultural areas
- **Manufacturing innovation**. E.g. Optimizing the use of materials through processes such as 3D printing; innovation in manufacturing, such as injection molding and extrusion of biomass feedstock, to accommodate new materials, like paper pulp and bagasse; creating processes that are scalable, low-cost and that use locally available materials.
- **Product Disposal/Recycling innovation.** Technologies and business models for collecting, sorting, reusing and recycling plastics that minimize generating waste or toxics. Innovations are needed to convert plastic waste into high-value base materials with sufficient purity to displace virgin materials in high-value uses.[12]

The term Circular Economy is currently often used to express the vision of sustainable materials management. This report emphasizes the chemicals perspective to reinforce the importance of addressing the impacts of chemicals and toxicity in facilitating a sustainable circular economy. The goal of this report is to identify and describe considerations and criteria that define sustainable plastics from the chemicals perspective. These descriptions will support those who select materials for product design as well as those who evaluate materials and purchase products based on sustainability claims. Sustainable product design is envisioned as a circular process that begins with establishing sustainable design goals and touches on every stage of the life cycle. Plastics should be considered within and across all life cycle stages and should be evaluated for continual improvement. Considerations and criteria described in this report may apply be applied as appropriate to one or more of the steps in Figure 1.

Figure 1. Steps to sustainable plastic design and continual improvement

2.0 EXCLUSIONS

- **Plastic versus non-plastic materials.** This paper does not include criteria for comparing the use of plastic to non-plastic alternatives that may be viable options for product design. For example, some computer manufacturers have moved away from the use of plastic to the use of metal casings for their products.
- **Engineering performance technical requirements.** Engineering requirements such as density, tensile strength, transparency, moisture barrier, impact resistance, etc. are not considered. They are within the realm of the designer's expertise. Materials must meet performance specifications or they will not be useful. The criteria in this overview are intended to supplement technical performance information leading to more sustainable plastics from the chemicals perspective. Sustainable plastics must perform well enough to replace less sustainable plastics or other materials.
- **Regulatory requirements.** Some plastics must meet regulatory requirements. For example, plastics used in medical devices and for food contact are subject to regulatory testing requirements. Regulatory requirements are mandatory and outside of the scope of these sustainable plastic design criteria; however, materials that do not meet regulatory requirements are unlikely to meet sustainability requirements, especially for toxicity concerns.
- **Economic criteria.** OECD SMM Policy Principle 3 calls for "using the full diversity of policy instruments to stimulate and reinforce sustainable economic, environmental and social outcomes." Policy instruments are addressed in related reports. Economic criteria are outside the scope of this report.
- **Social criteria and stakeholder engagement**. OECD SMM Policy Principle 4 calls for "engaging all parts of society to take active, ethically-based responsibility for achieving sustainable outcomes." Stakeholders should be considered in the development of sustainable plastics. This can be done by direct engagement and by consideration of who has power to influence products and who is impacted by them. While manufacturers have primary influence over chemical and material choices, other stakeholders can influence the ultimate success of products in the marketplace. Social criteria and stakeholder engagement are outside the scope of this report.
- **A prescribed decision framework.** While this report identifies key considerations and potential tradeoffs, it does not dictate which alternatives to choose. The focus is on comprehensive and meaningful criteria that can be used to evaluate plastics and to support informed decision-making. In alternatives assessments, decision analysis is used to determine preferable substances, materials or products. It can be helpful to choose a decision framework early in the evaluation, especially if there are clear priorities. Setting up an initial screen can save time and money. For example, a designer may eliminate options early on that do not meet degradability requirements. Alternatively, the designer may choose to retain all alternatives and to evaluate multiple criteria simultaneously once all the information is gathered. Regardless of the decision framework, the same criteria support decision-making.

3.0 SCOPING AND PROBLEM FORMULATION

Goal: To establish sustainable design priorities.

Before evaluating materials for chemistry-related sustainability criteria, the material chooser should first define their own product design and sustainability goals using life cycle thinking. Life cycle thinking (LCT) is used to consider potential impacts from plastics across the product life cycle. See Figure 2. It helps with problem scoping and informs all of the sustainability considerations identified in this report. The key aim of LCT is to identify life cycle stages where significant impacts occur and to highlight differences between alternatives. LCT helps to avoid burden shifting by identifying where changes at one stage of the life cycle, in one geographic region or in one impact category could result in increased impacts elsewhere. [13] LCT helps manufacturers and policy makers identify opportunities for improvements across the supply chain and through all the product life cycle stages and can be used to identify only those life cycle segments where significant impacts or significant differences from other plastics occur. More information on LCT can be found in the Interstate Chemicals Clearinghouse (IC2) and the California Safer Consumer Products alternatives assessment guides.[14,15] Mapping the life cycle stages of specific plastics supports life cycle thinking and a comprehensive approach to identifying sustainable product design goals

In contrast, life cycle assessment (LCA) provides quantitative assessment of differences between materials for a set of impact categories (See Appendix 8). Life cycle assessment can be used to evaluate impacts across the entire product life cycle or it can be scoped more narrowly to address limited life cycle stages and impacts. LCT can be used to identify those life cycle stages with meaningful differences between plastics and where more expertise, more data and more analysis using LCA will be most fruitful.

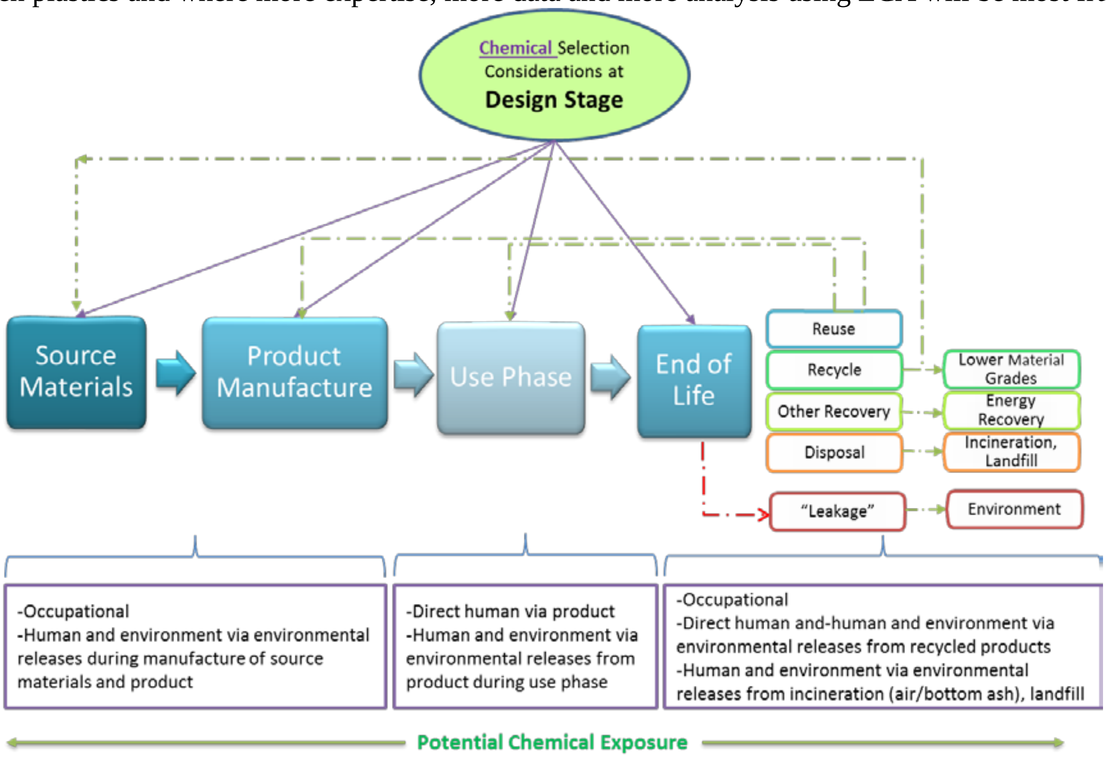


Figure 2. Life cycle stages for plastic products (OECD, unpublished)

3.1 Establish Product Design Goals

The choice of a plastic material is tied to its intended function. Plastics are used in thousands of applications in agriculture, footwear and apparel, toys, flooring, medical devices, packaging, etc. Sustainable product design goals should be clarified up front. For example, consider:

- *The intended product application.* Different applications require plastics that may have very different characteristics (e.g. flexible, rigid, etc.). Once functional requirements are met, the most sustainable solutions can be sought.
- *The intended durability and longevity of the product and how well it aligns with the durability and longevity of the plastic.* The use of a durable plastic in a long lasting product is likely to have life cycle benefits. Durable plastics in other applications may have benefits if the durability facilitates reuse and recycling.
- *Feedstock preferences such as preference for biobased or recycled content.* For example, a developer may seek to create a product that meets biobased procurement specifications.
- *Production/Manufacturing goals.* For example, a product developer may seek to develop a product with a lower carbon footprint than current products using life cycle thinking to avoid burden shifting.
- *Intended (and likely, but unintended) product users.* Identifying the intended users of the product helps to prioritize considerations for hazard and exposure. For example, a manufacturer may prioritize plastics that contain chemicals that are especially benign to the skin if the product is to be used in skin contact. Likely but unintended users, or potentially exposed populations including environmental receptors, should also be considered.
- *Product recycling objectives.* A manufacturer should have plans for the product after the end of its initial use. For example, a designer may design the product for disassembly and recycling within an existing public recycling infrastructure, or within a private product stewardship or 'take-back' program.
- *Market requirements.* Compliance with ecolabels, certification programs and industry sector voluntary initiatives can drive plastic selection. For example, some certification programs restrict the use of certain polymers (e.g. PVC) or additives (e.g. brominated flame retardants). In the apparel and footwear sector, Zero Discharge of Hazardous Chemicals coalition members agree to avoid chemicals on sector Restricted Substances Lists (RSLs) or Manufacturing RSLs (MRSLs).
- *Decision methodology.* It is helpful to consider how decisions will be made for material selection early on in the evaluation process. A decision method can dictate information needs and the criteria that will be applied moving forward. Some decision-making approaches are simpler than others to apply, use fewer resources and cost less to implement. Three decision methodologies used in the alternatives assessment (AA) process (i.e. Sequential, Simultaneous and Hybrid Methodologies) are described in Appendix 1. In general, the Sequential Method rules out options early in the assessment process. The Simultaneous Method is more comprehensive but more expensive to implement and requires more data. A hybrid approach can be used to first rule out options that do not meet design goals and then to compare remaining options using the simultaneous approach.

4.0 FEEDSTOCK

Goal. To use base feedstock that preserves natural capital (maximizes resource efficiency) while providing performance and sustainability benefits.

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.[16] Humans depend on natural capital for a wide range of ecosystem services. Poorly managed natural capital can destroy productivity and resilience, making it more difficult for humans and other species to sustain themselves. Sustainable Design Principles call for the preservation of natural capital (and resource efficiency) as an imperative. The choice of plastic feedstock can have significant impacts on natural capital. The goal is to decouple feedstock selection from negative impacts on natural (and societal) capital. Products based on non-renewable, non-recycled resources, degradation or consumption of renewable resources at rates faster than they can regenerate, or use of materials that degrade land or compete with food production are not sustainable. Using feedstock from recycled materials and plastics that are readily recyclable helps to link upstream material selection to downstream recycling options. Using readily available wastes, such as agricultural wastes, or rapidly renewable biomass, like algae or seaweed, can offset impacts from unsustainable practices. However, they require special attention for managing them for product disposal/recycling if they are not recyclable with more conventional plastics and risk contaminating recycling streams.

Define the primary feedstock used to generate the plastic. In general, rapidly renewable or waste-derived feedstock results in supply chain benefits. However, challenges exist such as ensuring there is infrastructure to recover and recycle the material and that bringing the product to consumers does not end up contaminating other plastics and subsequently lowering their recycling rates. Sustainability can be enhanced by linking waste products to feedstock to ensure both supply and demand for materials that cycle in a sustainably managed material economy.

Specifying materials with the following attributes supports the design of sustainable plastics. Document the use of:

- **Rapidly renewable feedstock.** Examples include sustainably grown and harvested, rapidly growing land-based crops or aquatic algae or seaweed. Preferred materials avoid the use of land that competes with social, ecological or food production value on the local, regional and global scale.
- **Waste-derived materials**:
  - Biobased agricultural wastes
  - Recycled material of sufficient purity that it can be re-recycled without loss of performance and without the propagation of toxic chemicals.
- **Readily recyclable plastics.** Plastics derived from non-renewable feedstock may support sustainable materials management as long as product design facilitates future recycling and the ongoing use of recycled materials.[17] Evidence of highly efficient recycling infrastructure should be evident before selecting plastics derived from non-renewable or recycled resources.

Use life cycle assessment to measure impacts from materials, energy and emissions.
While using rapidly renewable, waste derived and readily recyclable feedstock is intuitively beneficial, it is important to check assumptions. Biomass that is 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 assessment[18] and natural capital assessment.[19] While outside the scope of this report they deserve to be mentioned.

5.0 GATHERING CHEMICAL INVENTORY DATA

Goal: To identify chemicals used or generated during the production and manufacturing, use and disposal/recovery (end-of-life) life cycle stages.

Chemicals used and generated across the life cycle must be identified in order to assess hazard, exposure, and life cycle including disposal/recycling impacts from plastics. It can be challenging to assemble a complete chemical inventory. This is partly because formulations are often proprietary and partly because information across all life cycle stages may not exist or be available, even to manufacturers. *At a minimum, a chemical inventory should include all substances that may be retained in, or migrate from, the plastic including the monomer(s) used in manufacture and any known additives and residuals (impurities). Chemical transformation products that may be formed during likely disposal/recycling pathways should also be identified.* Chemicals to which exposures are likely, such as chemicals to which workers or users are exposed, should be prioritized for hazard assessment. While imperfect, this approach is pragmatic.

Table 1 Types of chemicals to inventory based on life cycle stage and function

Production and Manufacturing	Use	Product Disposal/Recovery
• Raw materials • Monomer • Oligomers • Catalysts • Polymer • Performance additives (anti-oxidants, colorants, plasticizers, UV stabilizers, flame retardants, compatibilizers, etc.) • Manufacturing and processing aids (solvents, auxiliaries, lubricants, mold release agents, cross-linkers)	• Monomer • Oligomers • Polymer • Additives • Catalysts • Residual performance additives and manufacturing or processing aids • Other known or potential impurities	• Chemical degradation products • Combustion degradation products • Mechanical degradation products • Biodegradation products

5.1 Identify chemicals used or created at each life cycle stage.

First, map the functions of chemicals used, produced and emitted at each stage in the life cycle. Then, seek to identify the specific chemicals used to provide those functions. Production and manufacturing of plastics may involve many unit processes as illustrated in Appendix 2, but at a minimum they will include monomer production, polymerization and compounded plastic production, including performance additives (Table 1). Mapping unit processes can help to identify the types of chemicals used throughout the plastic life cycle. If a plastic is made from recycled materials, special attention and testing may be needed to monitor for likely impurities such as plasticizers and flame retardants.

Most chemicals have multiple names and will need to be clearly identified using identification schemes 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 considered unique. However, some identifiers apply to general classes or groups of chemicals so 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 can help to refine the identity of the compound. The chemical inventory should include the:

- Precise chemical identity
- Chemical function
- Concentrations or amounts (estimates or ranges may be necessary)

5.2 Set disclosure requirements

Clear boundaries need to be set for determining which chemicals to evaluate. One strategy is to set a concentration threshold or *de minimis* level above which a chemical constituent should be evaluated. Selecting a threshold may depend in part on the chemical's hazard characteristics. For example, endocrine active substances may be hazardous at very low exposure levels and thus a low threshold may be needed. Safety Data Sheets provide precedent for using different disclosure levels. For example, chemicals that are carcinogens must be reported if present above 0.1% while non-carcinogenic toxic chemicals are disclosed if present above 1%.[20] Some certification programs (Cradle to Cradle) link certification levels to the weight percent of chemicals disclosed in a formula.

Strategies for prioritizing ingredients for disclosure and evaluation include but are not limited to:

- All intentionally used or added chemicals at any concentration at any life cycle stage
- All intentionally used or added chemicals at any concentration for one or more life cycle stages (e.g. production)
- All intentionally added chemicals plus residuals above a concentration threshold[21]
- Only those chemicals and residuals above a concentration threshold.

There is no one right answer for establishing disclosure requirements. Some people start with higher screening thresholds and work to lower thresholds as needed.

6.0 HAZARD ASSESSMENT

Goal: To understand human health and environmental hazards associated with chemicals identified in the chemical inventory.

Understanding the hazard profiles of plastics and their chemical constituents is necessary for informed decision-making. Hazard assessment may be performed at varying levels of depth and complexity. The first step is to determine the level of chemical hazard evaluation needed and the assessment method that will be used. Each method dictates its own data requirements. Several hazard assessment tools exist. The Organisation for Economic Cooperation and Development (OECD) created a Substitution and Alternatives Assessment Tool Selector.[22] Using this, interested parties can evaluate the hazard assessment tools available and determine which tool might best suit their need. The California Safe Consumer Products Alternatives Analysis Guide also provides a comprehensive list of methods and databases for chemical hazard assessment.[23]

6.1 Classify Individual Chemical Hazards

Chemical hazard assessment (CHA) methods range from comprehensive to screening. They differ based on the number of hazard endpoints evaluated and the depth to which each endpoint is evaluated. With increased depth of chemical assessment comes increased understanding of the human health and environmental hazards associated with a chemical and better knowledge of data gaps. However, increased depth of assessment also brings more requirements for data, time, expertise and cost. One challenge of CHA is that CHA results may vary depending on who does the work. This is true for all of the methodologies unless the assessment is under authoritative oversight (e.g. USEPA Safer Choice, REACH) to resolve conflicts.

Full chemical hazard assessment (CHA). Full chemical hazard assessments require expert review and interpretation of the scientific literature. When data are lacking for the compound of interest, chemicals with structural similarities may be used as surrogates using read-across methods. Computer modeling based on mechanisms of action and structure-activity relationships have improved in recent years with the implementation of the REACH program in the European Union which de-emphasizes animal testing. Emerging hazard screening protocols include high throughput screening such as the Tox 21 program at USEPA.[24]

Standardized methods for CHA typically include and expand on classification as defined in the Globally Harmonised System of Classification and Labelling (GHS).[25] For example the Design for the Environment Program Alternatives Assessment Criteria for Hazard Evaluation v2.0,[26] GreenScreen for Safer Chemicals[27] and the Cradle to Cradle hazard assessment[28] methods incorporate GHS hazard endpoints and supplement criteria for persistence (P), bioaccumulation potential (B) and endocrine disruption (EDC) into their methodologies which are not provided as stand-alone endpoints in GHS. Full details of the CHA methodologies are freely and publicly available on the websites of the organizations mentioned above. Table 2 provides a list of hazard endpoints typically included in comprehensive CHAs. An even more comprehensive set of hazard endpoints is provided by the California Environmental Protection Agency (CalEPA) in support of their Safer Consumer Products program.[29] CHA reports typically include a summary of the data, hazard classification results presented in a hazard table and in some cases an overall chemical benchmark score.[30] See example hazard tables in Appendices 3 and 4.

Intermediate CHA. Intermediate CHA methods limit the number of hazard endpoints considered and prescribe a limited set of data sources. For example, the Quick Chemical Assessment Tool (QCAT)[31] developed by the Washington State Department of Ecology is designed for use by small and medium enterprises with limited toxicological expertise.

Hazard list screening. Screening chemicals against regulatory and authoritative lists of chemicals with known or suspected hazards is a useful first pass and takes little time and expertise. These hazard lists are mapped to hazard classifications. Several software tools now facilitate structured list screening. The Pharos Chemical and Material Library and the Chemical Hazard Data Commons (powered by Pharos)[32,33] screen against GS List Translator and other significant lists such as the Substitute It Now (SIN) list,[34] and restricted substance lists (RSLs) and manufacturing restricted substances lists (MRSLs) developed by the automotive, apparel and footwear, textile and retailer sectors.

Table 2. Hazard Endpoints typically used in full Chemical Hazard Assessment Methods

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)

Ideally, comprehensive CHA reports would be readily available for every chemical; however, that is rarely the case. A pragmatic approach would entail looking first for existing publicly available comprehensive CHAs such as those in the Interstate Chemicals Clearinghouse Chemical Hazard Assessment Database.[35] The next step could be list screening. Chemicals classified as known hazards by authoritative bodies can be quickly identified using list-screening tools. Chemicals not on regulatory or hazard lists may be inherently safer, or they may just be less well-studied. In those instances, intermediate chemical hazard assessment screening may be informative. If results from intermediate screening are not definitive, then a full CHA may be needed. A full CHA provides information not only on what is known, but also on what is not known about chemical hazards and clearly identifies data gaps.

6.2 Evaluate Mixtures and Polymeric Materials

CHA methods provide insight into the hazards of individual chemicals. However, plastics are essentially mixtures of chemicals that include the base polymer, residual monomers and oligomers, additives and impurities, including residual reagents and processing aids. Only a limited number of approaches evaluate the hazards of polymeric materials. In several regulatory systems, polymer hazards are tied to low molecular mass materials that can leach from the bulk polymer or that are present at or above a threshold such as 1%. The implication is that there is a direct toxicity link between monomers and toxicity of the overall plastic.[36] Knowing the concentration and toxicity of residual monomers can help distinguish between plastics based on hazard. However, it is possible that other chemicals added to or present in the plastic could dominate the hazard profile of the plastic.

Standardized approaches to evaluating the hazards of plastics: Several certification programs exist that evaluate polymeric materials and either score the plastic or subject it to pass/fail criteria. Each program uses different concentration thresholds for reporting and scoring that are more or less protective and precautionary. Example include:

- **Globally Harmonised System for Classification and Labelling (GHS).** GHS provides rules for classifying chemical mixtures that can apply to polymers. GHS allows a mixture to be 'not classified' (low hazard) if it can be shown conclusively with experimental data from internationally acceptable test methods that the substance or mixture is not biologically available. Alternatively, individual ingredients may be classified for hazard and an algorithm used to calculate an overall classification. Limitations to GHS include that global implementation of GHS is currently limited and it does not include standalone hazard endpoints for endocrine disruption, persistence and bioaccumulation. These endpoints are needed to identify some Substances of Very High Concern (SVHCs).
- **Cradle to Cradle (C2C) Certification**: Polymers are evaluated based on their toxicity and are certified from high to low as platinum, gold, silver, bronze or basic. The C2C method evaluates products against criteria in five modules: Material Health, Material Reutilization, Renewable Energy & Carbon Management, Water Stewardship and Social Fairness. Overall certification is based on all five modules. The Material Health module can also be used as a standalone method to evaluate the plastics, and it incorporates exposure and "cyclability" considerations.[37]
- **The USEPA Safer Choice Polymer Screen**: The US EPA provides guidance to evaluate polymers and their degradation products for potential impacts on human health and the environment as linked to USEPA's Sustainable Futures Program.[38] A polymer that passes all requirements is assumed to be a safer alternative.
- **GreenScreen for Safer Chemicals v1.4**[39] includes a Polymer Assessment Procedure. Using this procedure, the polymer, monomers and oligomers and additives are assessed. It provides a process to generate a polymer Benchmark score that is distinguished from Benchmark scores for individual chemicals.

Customized approaches to evaluating the hazards of plastics: A product designer may choose to customize an approach to compare plastics based on hazards associated with substances in the plastic. For example, they may choose to calculate the percent composition of any SVHCs or on sector-based restricted substances lists. Alternatively, a designer may choose to compare plastics based on the presence (or absence) of chemicals with specific hazards that are relevant to their product design. For example, skin sensitizing chemicals would be undesirable for plastics used in wearable devices. Customized criteria for safer plastics may include but are not limited to:

- Plastics that contain no Substances of Very High Concern (SVHCs)
- Plastics that contain no substances identified as CMRs, PBTs, highly aquatic toxicants or any other hazards relevant to the use of the plastic

- Plastics that contain no substances that interfere with or contaminate recycling

Polymers of low concern considerations:
The United States, Canada, the European Union and other countries have established criteria and methods to screen for polymers of low concern.[40] 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 material including unreacted monomers and partially reacted oligomers.

Criteria for polymers of low concern are intended to protect human health from the regulatory perspective, but they do not address sustainability criteria such as feedstock or disposal and recycling considerations. Nor do they address problematic uses of plastics such as microbeads designed for direct release into wastewater. They address inherent polymeric toxicity and reactivity relevant to human health. Appendix 5 includes a USEPA template for collecting information on polymers. Appendix 6 includes a table that compiles current national criteria for polymers of low concern to include with hazard requirements for sustainable plastics.[41] Considerations of note address:

- Presence of low molecular weight substances (< 500 Dalton, 500-1000 Dalton) including monomers and oligomers. It is important to know the molecular weight ranges of substances in a plastic. Lower molecular weight substances are more likely to be able to migrate from plastic and if toxic, will result in exposure

  Additives of concern. Avoid the use of oxo-degradable additives. Avoid the use of any Substance of Very High Concern. Pay special attention to types of performance additives that have included chemicals of concern such as flame retardants, plasticizers and per and poly-fluorinated substances.

7.0 COMPARATIVE EXPOSURE ASSESSMENT

Goal: To evaluate exposure pathways across the product life cycle that might lead to increased risk to humans and environmental health and harmful waste.

Exposure to chemicals in plastics depends on the properties of the polymer, its chemical constituents and how those constituents are integrated into the plastic.[42] It also depends on how the plastic is used. It is useful to frame where exposure is most likely to occur to focus resources for exposure assessment where they are most needed. Not all alternatives will result in the same exposure scenarios. Ideally, both near-field (direct consumer) and far-field (environmental) exposures should be considered and applied to all life cycle stages of the plastic. It is important to include both potential human health and environmental exposures in the assessment.

7.1 Build a conceptual model or map of potential exposures across the product life cycle

Exposure mapping is used for risk assessment. Using life cycle thinking, identify where exposure to chemical ingredients or degradation products are most likely to occur and to whom. Identify susceptible individuals or populations and environmental receptors. Identify the most likely routes of exposure (oral, dermal, inhalation). Consider environmental fate and transport through, air, water, soil, sediment, etc. as well as exposures resulting from waste disposal and treatment. Consider exposure scenarios that are intended and those that can be reasonably anticipated to occur, even if the product is not designed for such use. For example, a child may mouth a plastic phone case. And products may be disposed of (i.e. littered) in undesirable ways resulting in exposure to air, water and soil.

7.2 Evaluate ingredient/product interactions

The mobility of plastics and substances within a plastic can determine its potential for exposure. For example, some flame retardants are chemically bonded to polymers which reduces their ability to migrate out. Other flame retardants are additive which allows them to migrate more freely. Evaluate:

- **The quantity of substance and frequency of its use.** The concentration of a substance in the plastic and the frequency of product use can impact exposure.
- **Intended use**. The intended use and reasonably anticipated misuse (e.g. children mouthing) of the product strongly dictates the exposure potential. In some cases, testing for extractability and leachability will be needed to assess exposure potential to substances in the plastic. Plastics designed for environmental release, such as microbeads, may be made from recyclable plastics, but based on use, there is not a real likelihood of recycling and their use will maximize exposure to the environment.
- **Plastic permeability**. 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.[43,44]
- **Environmental parameters**. Environmental parameters, such as the temperature at which the product is used, can affect the rates at which additives migrate from the plastic and how the plastic degrades. Identify any potential plastic degradation or other transformation products not already identified in the substance inventory.
- **Further processing.** Partially reacted polymers intended for further polymerization or plastics that will undergo further processing by users may lead to increased exposure. For example, plastics used for some types of additive manufacturing (e.g. 3D printing) may result in toxic emissions when the plastic filament is heated.

7.3 Inherent chemical properties

Chemical ingredients have varying chemical properties such as volatility, water solubility, reactivity and many others, resulting in different potentials for exposure.[45] Some physical properties listed in Table 3 are included in a comprehensive CHA, such as the octanol-water partition coefficient or persistence in various environmental media. Based on exposure mapping, identify situations where the inherent chemical properties of the substance in a plastic may determine significant differences in exposure.

Table 3. Exposure parameters based on inherent chemical properties

Criteria	Exposure Concern
Bioavailability	Ability of a substance to be absorbed and circulated in an organism (e.g. skin permeability, oral absorption)
Bioconcentration or bio accumulation factors (BCFs or BAFs)	Direct measurement of whether a chemical is bioconcentrating or bioaccumulating indicating increased exposure potential, primarily from food
Aqueous solubility	Increased solubility suggests increased potential exposure through aqueous media, etc.
Octanol-water partition coefficient (log K_{ow})	Indication of fat solubility; increased fat solubility suggests increased chance for bioconcentration or bioaccumulation
Persistence	Increased longevity suggests increased likelihood of long-term exposure. Consider persistence in air, fresh and marine water, soil, sediment and in sewage treatment.
Melting point	Tied to usage
Boiling point	Increased volatilization
Vapor pressure	Increased volatilization
Molecular weight	Smaller molecular weights may increase likelihood of bioavailability.
Henry's Law constant	Indicates how much of a chemical escapes to the gas phase. The higher the constant, the greater the potential for exposure via inhalation.
Particle size distribution	Tied to potential inhalation exposure, i.e. smaller particles are more likely to enter and penetrate the lungs, skin, etc.
Skin permeability, log K_p	Higher skin permeability could result in greater dermal exposures.
Soil sorption partition coefficient, log K_{oc}	Increased soil adsorption may suggest less migration and bioavailability and more exposure to soil organisms.
Octanol-air partition coefficient (log K_{oa})	Indication of fat solubility; increased fat solubility suggests decreased chance for release to the air

An example of a comparative exposure assessment can be found in Appendix 7.

8.0 PRODUCT DISPOSAL AND RECYCLING (END OF LIFE) CONSIDERATIONS

Goal: To maximize resource efficiency and to eliminate waste, hazards and pollution associated with the fate of plastics after use; and to guide product designers in 'designing with the end in mind'.

For sustainable plastics management within a circular economy, feedstock selection, production and manufacturing, use, and product disposal and recovery options are interconnected in an efficient and beneficial way. Feedstock selection is at the 'upstream' end and product disposal and recycling are at the downstream end and they are connected through chemical and material selection and product design. There are many variables: Different countries and jurisdictions have different requirements for product packaging standards and different waste management practices. The inherent properties of the plastic enable different disposal and recycling options. Some 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 recycled material. The product designer should think through these possibilities and 'design with the end in mind' including considering the impacts of the materials selected.

8.1 Define a credible waste management plan for the plastic in the product

Product design should include available plan for recovering and recycling the plastic after use. The plan may take advantage of publicly accessible waste management infrastructure. Or it may involve a closed and privately managed system based on product stewardship. The plan should account for regional differences.

- **Identify the waste management pathways that the plastic can inherently undergo**.
    - Reuse. Identify opportunities for reuse and repair to increase product longevity. Keeping plastics from becoming waste is a top priority.
    - Recyclability. Identify the kind(s) of recycling that are feasible for the plastic (e.g. primary, secondary, tertiary).
    - Biodegradability.
        - Inherent biodegradability of the chemicals in the plastic. Includes biodegradation in air, water, soil and sediment under aerobic and anaerobic conditions as defined in most chemical hazard assessment persistence classification methodologies.
        - Composting. Example certification programs include:
            - Commercial standards such as the harmonized European standard EN 13432 and EN 14995 (for non-packaging items)
            - Home (backyard) standards such as the DIN CERTCO (Germany) and Vinçotte (Belgium)
        - Marine degradability standards such as ASTM D7991. Marine biodegradability could be a desirable feature to mitigate a worst-case scenario but should not be presented as waste management pathway.
- **Identify available waste management infrastructure options wherever the product is sold.** Identify the types of waste management infrastructure that are available where the product is sold. This will vary between regions. Include:
    - Leakage (improper management, litter)
    - Landfill
    - Incineration with no energy recovery
    - Incineration with energy recovery
    - Recycling (primary, secondary, or tertiary)[46]
    - Compost (commercial)

- Compost (backyard)

- **Evaluate the likelihood that the product will undergo various disposal or recycling options.** Besides the availability of infrastructure, the likelihood of a plastic product undergoing a designated disposal recycling pathway is tied to the intended longevity and durability of the product, the value of the product, cultural norms, etc. Treat leakage as a worst-case scenario. To estimate how likely it is that leakage to the environment will occur, global statistics based on types of plastic waste found in the environment and released from different countries and regions can be a proxy. Regional differences are important to consider and should inform design.
- **Other product stewardship.** The waste management plan should address how to recover the plastic and options for reuse, recycling, etc. It should also communicate this information to customers. For example, Green Blue Institute has developed the How2Recycle Labeling program to assist with optimizing proper product and recycling management of packaging materials. [47] If public infrastructure for recycling of a plastic is not available, describe other plans for product stewardship.

8.2 Understand the impacts of various disposal and recycling options for the material

It is important to understand both the relative impacts of a waste management technology alone (e.g. CO_2 emissions from incineration) and the potential impacts of the material when it undergoes a waste management technology (e.g. material specific toxic emissions). While the waste hierarchy has served as a rough guide to prioritizing waste management pathways, life cycle assessment may prove exceptions to the rule.

- **Impacts of the technology itself.** Ranking of plastic disposal and recycling options has been performed using LCA. From a human health perspective, recycling (best)> incineration with energy recovery >landfill. [48] From the greenhouse gas perspective, recycling (best) >waste to energy>wastewater treatment>composting>landfill >incineration. [49] These results may vary on a case specific basis.
- **Material-specific impacts of waste management technologies.** Given knowledge of the plastic and substances in it, predict transformation products that may be formed when the plastic undergoes each likely treatment pathway and identify potential impacts from those transformation products. For example, plastics containing organohalogens will form combustion by-products like HCl, HF and potentially dioxins under non-ideal conditions. Then identify potential impacts. If a food container is commercially compostable and contains a persistent additive, the additive may contaminate the compost and lower its value. Certain transformation products are well known (e.g. dioxins, inorganic salts) and require management.
- **Evaluate the potential for beneficial material recovery.** Consider whether or not a plastic can be recycled multiple times. Prioritize opportunities for reuse and for multiple cycles over one time energy recovery. Plastics that are the most energy intensive to produce may have the greatest life cycle benefits when recycled. Consider carefully the chemicals in the plastic to determine whether or not their presence will lower the value of the resulting material and potential for future cycles due to contamination.

8.3 Optimize design for disposal and recovery

Consider possible design or material changes to improve the overall results. The RecyClass Tool [50] developed by Plastics Recyclers Europe was developed to guide the choice of plastic in packaging and to promote 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 addresses the presence of incompatibilities that affect the efficiency of recycling. Plastics that are 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. RecyClass is limited to a small variety of plastics such as PET-bottles, PE-LD and -HD, polyolefin tubs and trays, etc. 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. A few guidelines for product design based on disposal and recycling impacts include:

a. **Couple disposal and recovery plans with feedstock selection.** The choice of **f**eedstock is a design choice and may determine waste treatment options. Choose materials that are recycled and that can be further recycled. Consider linking rapidly renewable biobased feedstock to readily compostable products.
b. **Ensure the plastic can be easily separated**. Avoid composites for which there are no beneficial recycling options.
c. **Avoid additives that degrade the quality of recycled plastic**. Chemicals of concern in plastics will come back to haunt efforts for a circular economy.
d. **Select plastics that can have the best disposal and recycling profiles.** For example, prefer plastics that can be recycled multiple times; plastics that with the fewest negative impacts from waste management, and plastics with multiple options for waste management pathways to allow for variability between regions with different waste management infrastructure and cultural norms.
e. **Design to mitigate worst-case waste disposal and recycling scenarios.** While no product manufacturer intends their product to become litter, leakage happens. Design the product so that if leakage occurs, the impacts are mitigated.
f. **Provide instructions for proper waste management.** Raise awareness, minimize confusion, and communicate guidance throughout the supply chain.

9.0 WHOLE PRODUCT ASSESSMENT

Goal: To maximize resource efficiency and to eliminate the use and generation of toxic chemicals and pollution over the entire life cycle of the product; to drive innovation and not just incremental improvements.

Evaluating criteria for safe and sustainable plastics can be considered at each life cycle stage and should also be considered across the entire product system. As mentioned previously, a plastic may be made using relatively benign monomers and additives and it may be inherently recyclable, but if it is designed for use as micro beads in a body wash product that is released to wastewater —and subsequently to the environment — then it cannot be considered sustainable. The goal is to optimize for all of the sustainable design principles. Evaluation of each life cycle stage can help point out 'hot spots,' or areas where there is room for improvement. Evaluation of the whole product system is essential to compare the use of the plastic in one product to another based on the service that the product provides. Rather than comparing one single-use, disposal plastic product to another it may be more beneficial to consider the service that product provides and other strategies to provide that service. For example, GO Box is a start-up business that created a *reusable* plastic food container that is being used to eliminate single use food packaging waste from take-out food from food trucks in Portland, Oregon and San Francisco, California via an innovative business model.[51]

GO box plastic is lightweight, durable and recyclable polyethylene. The boxes need to be lightweight because they are transported by bicycle. They also need to be durable to maximize the number of times they can be washed and reused. And, they needed to be of a size and shape that is familiar to food vendors. Polyethylene plastic best fit the requirements. Food vendors sign up and pay to use Go Boxes. Go Boxes contain QR codes. Clients use a phone app to assist with tracking and recovery of the boxes at convenient "drop sites" where the QR codes are scanned. The boxes are used until they fail and then Go Box recycles them.

If these entrepreneurs had focused only on materials, they may have overlooked the potential for the GO Box concept. Designers who wish to create sustainable solutions have an opportunity to develop disruptive innovations. Disruptive innovations are new products that provide the same function as old products but in a very different, and potentially much improved, way. Life cycle thinking can be used to identify products or services that need additional or deeper evaluation, opportunities for innovation and improvement or where there is an opportunity for an entirely new product to excel. And life cycle assessment and related tools can be used to confirm sustainability benefits.

As with any product, all potential human and environmental health impacts associated with inputs and releases from each life cycle phase should be assessed. The results will make it clear whether or not the product innovation is truly a preferable alternative.

10.0 EVALUATION AND OPTIMIZATION

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

In this report, sustainable design principles were presented to encourage a holistic approach to product design from the view of chemical and polymer selection. Product design as a creative endeavor requires tradeoffs. While tradeoffs are inevitable and challenging, there are different ways to manage them.

- **Transparency**. Wherever there are tradeoffs, transparency can support credibility and ensure that decisions are clear and understandable. Tools that are 'black boxes' are not recommended because it will not be clear if the results aligns with the stated goals and objectives of the product designer. Transparency about chemicals in products supports consumer trust and informs decision-making.
- **Set baseline requirements**. While tradeoffs may be necessary, baseline limits can be set so that gains in one category do not result in unacceptable losses in another. For example, while effective recyclability and available recycling infrastructure are desirable, they are not viable tradeoffs for plastics that violate a design objective to avoid plastics containing substances of very high concern.
- **Prioritize criteria based on sustainable design goals.** Based on the initial problem formulation, the material selector should identify plastics that best meet their design goals. Depending on the available options, the product design goals may be modified to mitigate negative impacts.
- **Criteria weighting.** In a perfect universe, an alternative would be optimal for all categories, i.e. low hazard, low energy consumption, high recyclability or degradability, etc. However, this is rarely the case and trade-offs have to be made. Tradeoffs arise both between and within categories. For example, within hazard assessment alone, additives may not be substances of very high concern, but they may still be hazardous to humans or the environment based on other hazard traits. Fortunately, chemical hazard assessment methods are becoming increasingly standardized to allow for transparent tradeoffs. Tradeoffs between categories may also need to be made. 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 considerations and avoids potential perverse outcomes by focusing on only one or two.
- **Data gaps.** Filling data gaps can be time and resource intensive. All considerations identified in this report are subject to data challenges and subsequent uncertainty. For example, it may not be possible to identify every chemical used or included in the plastic and every degradation product formed. Therefore focusing on those life cycle stages where the greatest exposures to humans and environmental hazards are likely to occur should be prioritized. Data gaps in hazard information are also likely. A tiered approach to hazard screening that begins with hazard list screening and moves to more comprehensive chemical hazard assessment is appropriate.

11.0 CONCLUSIONS

The intent of this report is to propose a holistic, principle-based set of considerations and criteria for sustainable plastics from the chemicals perspective that are meaningful and actionable and that will trigger thoughtful discussion and further refinement. Improved consensus on these considerations and criteria will lead to better understanding of how to apply existing tools and metrics and where additional tool development and research are needed.

Appendix 1: 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, the 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 both 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 benefits of the Sequential Methodology are that it 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 the data collected, all of the alternatives are compared against the desired criteria simultaneously. 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.

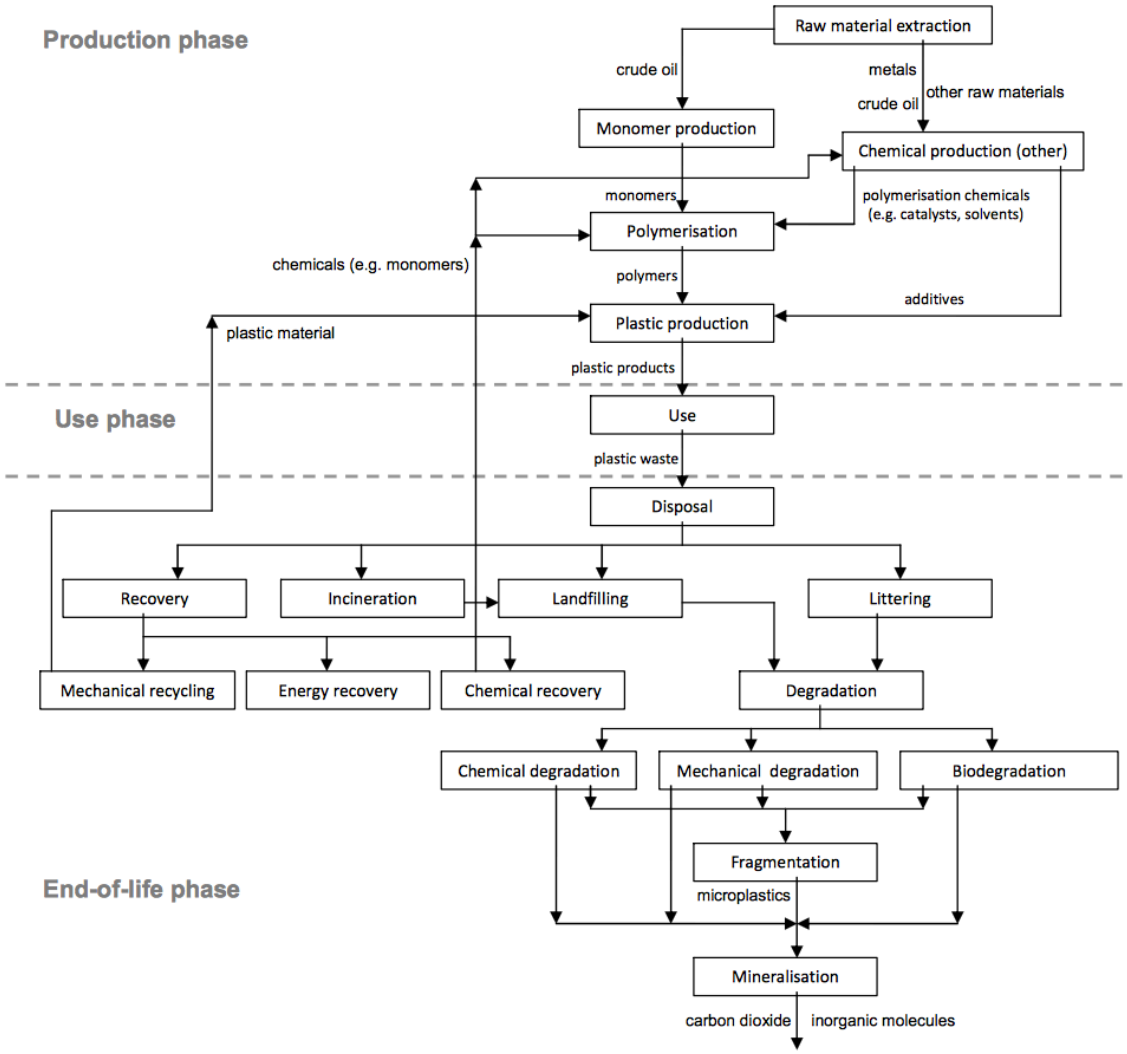
Hybrid Methodology. The Hybrid Methodology, as its name indicates, is a mixture of the Sequential and Simultaneous Methodologies. In the Hybrid Methodology, the Sequential Method is used for a few criteria and the alternatives that remain at the end of that process are subjected to further evaluation using the Simultaneous Methodology. For example, an organization may decide to use the Sequential Method for the performance and toxicity evaluations. Only those polymers or polymer classes 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 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 2: Example Unit Processes in the Life Cycle of a Plastic Product

(excluding energy and emissions)[52]



Appendix 3. An example USEPA Design for the Environment Chemical Hazard Assessment Table[53]

The USEPA Design for the Environment (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 font to indicate levels of confidence in the hazard classification levels. This hazard table was produced for an alternatives assessment done by the USEPA Design for the Environment Program to evaluate alternative flame retardants to DecaBDE.

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 4. An example GreenScreen Chemical Hazard Assessment Table and Benchmark Score

Benchmark Chemicals

In addition to summarizing hazard classifications by endpoint, GreenScreen also provides an overall chemical benchmark score ranging from Benchmark 1 (Chemical of High Concern) to Benchmark 4 (Safer Chemical). The GreenScreen 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. [54]

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

GreenScreen® Assessment View source View key

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

GreenScreen® Benchmark Score View key

Benchmark 2	Assessment Level
Moderate Concern	

Appendix 5. Data Collection Template for Assessment of Polymers[55]

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. Sustainable Futures Summary Assessment. Updated June 20

Appendix 6. Polymer of Low Concern Considerations[56]

Information on health and environmental hazards of the polymer	This includes hazard classification according to the UN GHS or any relevant national legislation and/or toxicity results from tests on the polymer.
Polymer class	Work by the OECD[57] *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).[58] 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.[59]
Performance additives of concern	Oxo-degradable additives: Plastics should not contain oxo-degradable substances. Oxo-degradable additives accelerate the fragmentation of plastic into microplastics but do not accelerate biodegradation of inert plastics. They may also adversely impact recycling. Certain phthalate chemicals: When used as plasticizers phthalates can be hazardous and considered to be enough of a risk to human health and the environment to warrant their restriction. Certain flame retardants**:** Polybrominated diphenyl ethers, for example, have been restricted or banned. Evaluation of alternatives is important for any assessment process, but special oversight is needed when these performance additives are used.
Highly fluorinated chemicals	Highly fluorinated chemicals are commonly used as mold-release agents for injection molding. While longer chain per- and poly-fluorinated substances known as C8 chemicals are of particular concern (persistent, bioaccumulating and toxic) to local and international governments, evidence is growing that the shorter chain molecules (i.e. C6s and C4s) may not be preferable alternatives.

Appendix 7. Example of a Comparative Exposure Assessment[60]

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 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.	Physical state			=	
Flammability and explosive potential: decaBDE is not flammable. RDP and TPP are flammable, but at high temperature. None of the three chemicals are explosive.	Log K_{ow}	+			
	Water Solubility	+			
	Flammability		-		
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.	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. Overview of 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.[61] LCA methodology is typically used in a comparative way. Results vary depending on how the system boundaries are defined. It is often used to find 'hot spots' or areas of greatest impact to identify and target opportunities for improvement. An LCA includes:

- Establishing the goal and scope of the assessment
- 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 help make an informed decision.

LCA can provide a comprehensive picture of the impacts that a chemical, product or process has on aspects of human health and the environment and can help to manage tradeoffs. It is also an important tool that can be used to check assumptions. Given the scope and depth of a standard LCA, the biggest challenge can be data availability and understanding the most 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[62]: Estimates the materials and energy resources required for and the environmental emissions resulting from activities in our economy
- GaBi[63]: Life cycle assessment software
- SimaPro[64]: 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 is to limit the scope of the system boundary. Another is to limit the number of aspects and impacts to evaluate. Life cycle thinking (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. The basic tenets behind LCT[65] are:

- To think about a chemical/product/process not as a single, static, entity but as a dynamic continuum that starts with raw materials and ends with an disposal or recycling scenario.
- To avoid undesirable burden shifting from one stage in a product life cycle to another due to changes in product formulation or design.
- To look at product impacts from a cradle-to-grave (or "Cradle-to-Cradle") perspective and to identify potential environmental, economic, or social impacts for each life cycle phase, in order to foster choices that support innovation and benefits over the full life cycle.

The following approach to using LCT and LCA is recommended:

Begin with life cycle thinking (LCT). Identify where life cycle impact differences between plastics are likely to be more or less substantive. For example, feedstocks selected for a base polymer can have very different life cycle impacts.

- Identify hot spots
- Identify opportunities for improvement across the life cycle.

Obtain standardized, certified LCAs for plastics with a focus on those impacts that are likely to be substantively different. For example, base polymers are typically derived from petroleum or biobased feedstock. Use of a biobased feedstock does not necessarily result in lower life cycle impacts, especially if there is heavy use of water or pesticides.

- Identify hot spots and compare the base polymers for different plastics. LCA is commonly used to compare materials and products for energy including the emission of CO_2 and the use of fossil fuels. Many LCA impacts stem from energy usage and associated impacts as measured using LCA.
- Identify opportunities for improvement across the life cycle. For example, consider how sourcing feedstock from local sources may improve the overall LCA results. Consider how using recycled feedstock rather than virgin feedstock might improve overall LCA results. Polymers that are the most energy intensive may be those that benefit most from recycling.

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