CHAPTER 2

Why Plastics

The image of plastics and the environment and human health is a complex one. On its surface, the immediate perspective is one of plastic waste. Images of plastic bags caught in trees and vegetation across the landscape, gyres of plastics in the oceans, whales caught in plastic netting, beaches littered with plastic debris disgorged from the ocean, and skeletal seagull remains filled with plastic beads. Plastic waste is a story of the persistence of plastic—powerful polymers resisting the degradation powers of the environment, enabling them to travel the globe and to wreak havoc on humans and wildlife. Increasingly the image of plastic waste in aquatic environments is growing more complex as plastic fragments collect toxic chemicals onto their surface and as finely degraded bits of plastics find their way into the tissues of aquatic organisms. As one scientist has stated "One of the most ubiquitous and long-lasting recent changes to the surface of our planet is the accumulation and fragmentation of plastics" (Barnes, et al., 2009).

It is more challenging to see the role of plastics in polluting people and the planet with chemicals of high concern (CoHCs). Much smaller than the smallest particles of plastics found in aquatic organisms, chemicals such as phthalates, Bisphenol A (BPA), and brominated flame retardants are invisible to the naked eye. Yet plastics play the largest singular role of any material in the global use of hazardous chemicals, with sizable impact on human health and the global environment.

This chapter starts by tracking the material flows of fossil fuels into chemicals and on into

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plastics, documenting the sheer volume of raw materials, chemicals, and CoHCs consumed by plastics. The chapter then turns to the human health and environmental implications of CoHCs in plastics across their life cycle and finishes with leading business initiatives to advance safer chemicals in plastic products.

Material Flows—from Fossil Fuels to Chemicals to Plastics

Plastics drive the chemicals economy. To the extent that green chemistry is a goal for the chemicals economy, its achievement will only occur if plastics are made from inherently less hazardous chemicals.

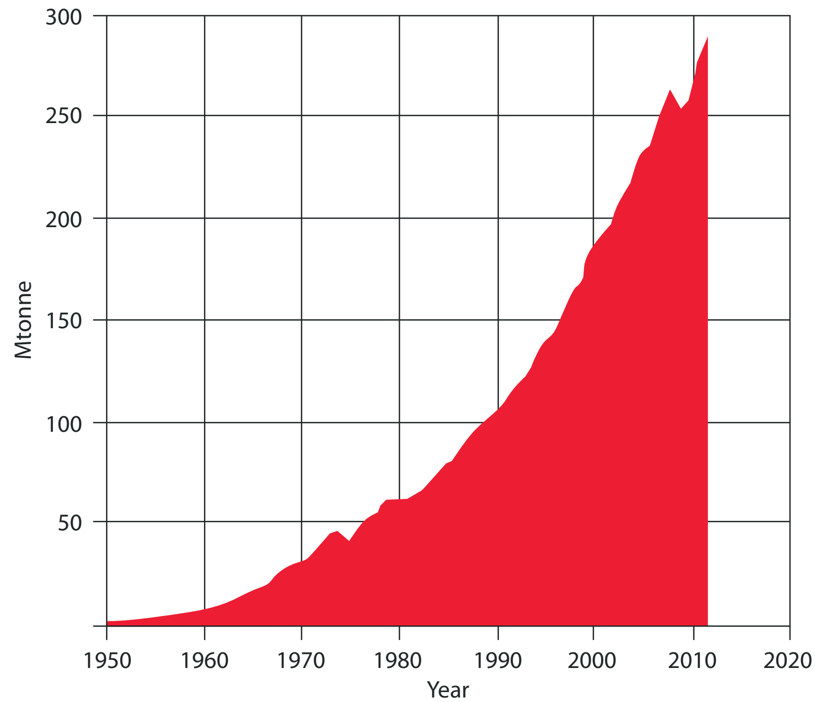
Synthetic plastics are a newcomer to the family of materials manufactured and used by humans. Over the past 70 years, plastics grew from a bit player in the material economy—with less than a million pounds produced globally in 1944—to a material behemoth, with global production at 288 million metric tons or 634 billion pounds in 2012. Figure 2 depicts the rapid growth of plastics in the global economy following World War II.

Producing those 634 billion pounds of plastics requires a huge input of resources beginning with fossil fuels. Around 4% of world oil and gas production is used as a feedstock for plastic production and a further 3–4% is used as energy in their manufacture (Hopewell, et al., 2009). From the crude oil and natural gas come chemicals, many of which are CoHCs to human health or the environment. These chemicals in turn are converted into plastics. The material flow for plastics, from crude oil and natural gas, to chemicals, to final product is huge (see Table 1 and Figure 3).

The plastics manufactured in the greatest volume globally are polyethylene,[4] polypropylene, polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene, acrylonitrile butadiene styrene (ABS), and polycarbonate. Together these seven different plastics accounted for 77% of total global production in 2012 or

4 Plastics manufacturers produce three different grades of polyethylene: high density polyethylene (HDPE), linear low density polyethylene (LLDPE), and low density polyethylene (LDPE).

FIGURE 2 **World Plastics Production 1950–2012**



Includes thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants and PP-fibers. Not included PET-, PA- and polyacryl-fibers.

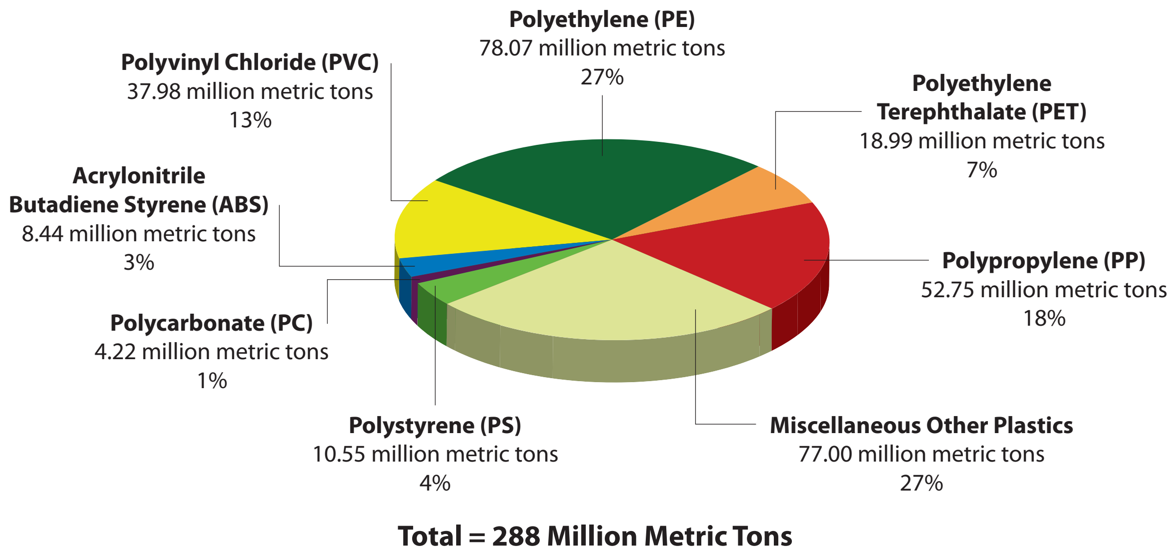
Source: Plastics Europe, 2013.

TABLE 1 **Primary Chemicals Consumed by Plastics**

Primary Chemicals	Total Global Consumption—All End Uses (million metric tons)	Consumed by Plastics (%)	Consumed by Plastics (million metric tons)
Ethylene[a]	113.18	84%	95.13
Propylene[a]	74.90	82%	61.66
Xylenes[b]	42.89	88%	37.62
Benzene[a]	39.67	85%	33.52
Chlorine[c]	56.21	42%	23.55
Butadiene[a]	9.28	94%	8.75
Methanol[a]	41.86	10%	4.19
Total	**377.99**	**70%**	**264.41**

"Primary chemicals" are the building block chemicals used to manufacture plastics and other chemicals.
a. 2008 data, b. 2009 data, c. 2010 data
Source: Chemical Economics Handbook, articles (a), (d), (e), (i), (j), (r), (s).

FIGURE 3 **Global Production of Plastics (2012)**



Sources: Plastics Europe, 2013; Sagel, 2012.

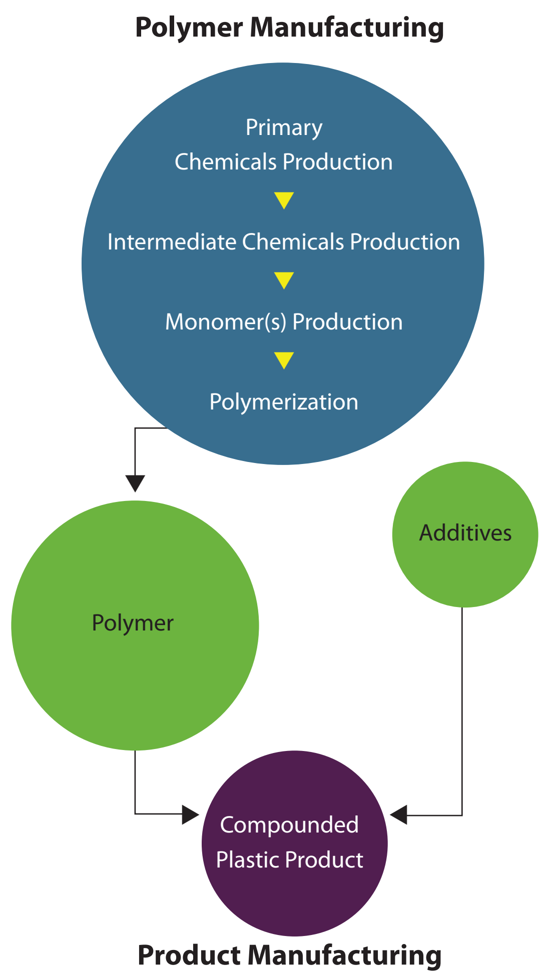
211 million metric tons; with the remaining 23% or 77 million metric tons spread across miscellaneous other plastics such as nylon, polyurethane, silicone, and styrene butadiene rubber (see Figure 3).

The production of plastics involves a series of steps that begin with fossil fuels (see Figure 4). While fossil fuels are the dominant raw material resource for plastics, manufacturers can also use biobased resources to produce plastics including corn, sugar cane, algae, waste methane from landfills, etc. The potential of using various bio-based resources for manufacturing chemicals for plastics are as diverse as our ecosystems.

From fossil fuels the next step on the manufacturing journey to plastics is primary chemicals—building block chemicals from which many other chemicals are derived. Table 1 lists the primary chemicals as well as the percent consumed by plastics. Ethylene, propylene, xylenes, benzene, chlorine, butadiene, and methanol are building block chemicals. Roughly 70% of annual primary chemical production, or approximately 264 million metric tons of primary chemicals,[5] eventually finds its way into plastics.

5 Note that the data points are for multiple years, thus 264 million metric tons is a rough approximation of chemicals consumed per year in 2008 and 2009.

FIGURE 4 **Steps in Manufacturing a Plastic Product**



The next steps in plastics production after primary chemical production (depicted in Figure 4), are the manufacture of intermediate chemicals, which are converted into monomers, which are then linked together into long molecular chains called polymers. In Figure 4 these steps are rolled up into the circle labeled "polymer manufacturing." Table 2 details the primary chemicals, intermediate chemicals, and monomers used to manufacture the plastics produced in the greatest volumes and highlights in red those chemicals that are CoHCs.[6]

Similar to the primary chemicals listed in Table 1, the volume of chemicals consumed at each of the other steps in polymer manufacturing—intermediate chemicals and monomers—is hundreds of millions of metric tons per year globally. Of the CoHCs consumed in the steps of polymer manufacturing, plastics consume 90% of those chemical markets or approximately 244 million metric tons per year as detailed in Table 3.[7] Among those CoHCs are well known, highly hazardous chemicals, including benzene, Bisphenol A (BPA), styrene, and vinyl chloride monomer (VCM). Note the 244 million metric tons or 536 billion pounds is a minimal estimate as it does not include all the CoHCs used in the manufacture of all plastics, including additives, as well as the fact that the data are from 2008 and 2009, in the midst of the great recession. See Appendix 1 for a detailed list of the health hazards of the chemicals listed in Table 3.

Polymers are then mixed (called "compounding") with additives to impart the unique properties needed in specific products (see Figure 4). Typical additives include flame retardants, plasticizers, antioxidants, antistatic agents, and colorants. Plastic compounding is the process of mixing or blending polymers and additives in a molten state to achieve desired properties. Once all processing steps are complete, the material is cooled and extruded into pellets,

6 The Plastics Scorecard uses the same criteria as BizNGO (2008) for defining chemicals of high concern.

7 Note that the data points are for multiple years, thus 244 million metric tons is a rough approximation of chemicals consumed per year in 2008 and 2009. Given those were recession years, this is a lower estimate of total consumption of CoHCs by plastics.

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TABLE 2 Plastics and the Chemicals they Consume

Steps in Polymer Manufacturing	Plastic Polymers							
Core Chemical Inputs	**ABS**	**PC**	**PE**	**PET**	**PLA**	**PP**	**PS**	**PVC**
Primary Chemical Inputs								
1,3-Butadiene	■●							
Benzene	■●	■●					■●	
Chlorine		■●						■●
Ethylene	●		●				●	●
Glucose					●			
Methanol				■●				
Propylene	●	●				●		
Xylenes (p-Xylene)				■●				
Intermediate Chemical Inputs								
Acetic acid				●				
Acetone		■●						
Ammonia	●							
Cumene		■●						
Dimethyl terephthalate / Terephthalic acid				●				
Ethylbenzene	■●						■●	
Ethylene dichloride								■●
Ethylene glycol				■●				
Lactic Acid					●			
Phenol		■●						
Monomer Inputs								
1,3-Butadiene	■●							
Acrylonitrile	■●							
bis(2-hydroxyethyl) terephthalate				●				
Bisphenol A (BPA)		■●						
Ethylene			●					
Lactide					●			
p-tert-Butylphenol		■●						
Propylene						●		
Styrene	■●						■●	
Vinyl chloride monomer								■●

ABS = Acrylonitrile Butadiene Styrene
PC = Polycarbonate
PE = Polyethylene
PET = Polyethylene Terephthalate

PLA = Polylactic Acid
PP = Polypropylene
PS = Polystyrene
PVC = Polyvinyl Chloride

■ Chemical of High Concern to human health or the environment

● Chemical is an input in the manufacture of the indicated polymer which are then packaged for distribution or sale to companies that will re-melt and mold the pellets into plastic parts or products (see Figure 4 for a shorthand version of those steps).

Human and Environmental Exposure to CoHCs in Plastics

Human and environmental exposure to chemicals related to plastics occurs every day. With plastics ubiquitous in manufacturing facilities, offices, cars, homes, and yards, people and the environment are exposed every day to the chemicals that break free from plastic products. Natural degradation forces—sunlight, oxygen, heat, abrasion—release residual monomers (monomers remaining in the product from incomplete polymerization) and the additives (incorporated into the polymer during compounding) into the environment, which then make their way into wildlife and people through the air, dust, water, and food.

While pure plastic polymers, long chain molecules without additives, are typically not regarded as hazardous, there is significant and growing evidence that many of the chemical building blocks and additives currently used to make plastics so versatile are also highly hazardous to humans and the environment (Meeker, et al., 2009; and Oehlmann, et al., 2009). For example, PVC as a pure, standalone polymer without the additives necessary to make it useful in a product, without considering the

TABLE 3 Plastics and the Chemicals of High Concern they Consume

Chemicals of High Concern (plastics)	Total Global Consumption (million metric tons)	Consumed by Plastics (%)	Consumed by Plastics (million metric tons)
Ethylene dichloride (PVC)[b]	43.45	97%	42.14
para-Xylene (PET)[b]	42.89	88%	37.62
Benzene (PS)[b]	39.67	85%	33.52
Vinyl chloride monomer (PVC)[b]	32.79	97%	31.80
Ethylbenzene (ABS, PS)[b]	27.57	99%	27.29
Styrene (ABS, PS, SAN, SBR)[b]	23.63	91%	21.38
Ethylene glycol (PET, Nylon)[a]	21.00	80%	16.80
Cumene (PC)[b]	12.23	84%	10.27
Butadiene (ABS, SBR)[b]	9.28	94%	8.75
Acrylonitrile (ABS)[a]	5.35	96%	5.16
Phenol (PC)[c]	8.90	55%	4.88
Bisphenol A (PC, epoxy resins)[c]	4.04	96%	3.86
Acetone (PC)[d]	5.67	45%	2.53
Total	**270.79**	**90%**	**243.48**

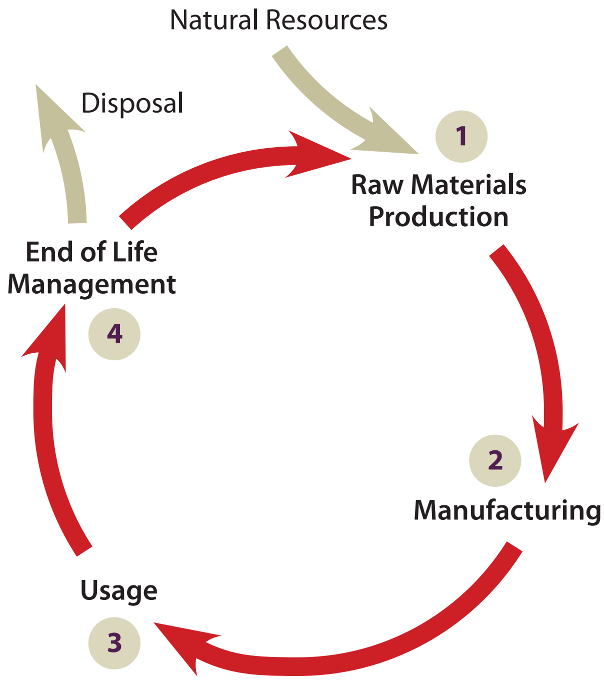
"Chemicals of High Concern" to human health or the environment = carcinogen, mutagen, reproductive / developmental toxicant; persistent, bioaccumulative, toxicant (PBT); endocrine disruptor; or chemical of equivalent concern.

Source: Chemical Economics Handbook articles (c), (d), (e), (f), (g), (l), (m), (n), (o), (p), (q), (s), (t).

ABS = Acrylonitrile Butadiene Styrene
PC = Polycarbonate
PE = Polyethylene
PET = Polyethylene Terephthalate
PLA = Polylactic Acid
PP = Polypropylene
PS = Polystyrene
PVC = Polyvinyl Chloride
SAN = Styrene Acrylonitrile
SBR = Styrene Butadiene Rubber

Source: Chemical Economics Handbook

FIGURE 5 **Life Cycle Stages of a Plastic Product**



chemicals used in its manufacturing, or without considering its end of life impacts, is typically considered a non-hazardous material. But once the building block chemicals of PVC (for example, vinyl chloride monomer) and additives like the plasticizer di(2-ethylhexyl) phthalate (DEHP) and the stabilizer lead are considered, PVC is no longer a benign polymer.

Figure 5 depicts the four primary stages of the life of a plastic product: raw materials production (usually fossil fuels), manufacturing, use, and end of life management. At each stage in the life cycle of a plastic product beyond raw material production, human and environmental exposure to chemicals related to plastics occurs. This section briefly examines the chemicals and health concerns that arise from exposure to CoHCs related to plastics manufacturing, use, and end of life management.

Exposure to CoHCs from Plastics during Manufacturing

Recent epidemiological data points to major occupational health concerns related to plastics manufacturing. A 2011 review of the epidemiological and toxicological literature funded by Health Canada explored the occupational exposures in producing plastics and the potential health risks particularly to a heavily female workforce in this sector (De Matteo, et al., 2011.) The review:

> demonstrates that workers are exposed to chemicals that have been identified as mammary carcinogens and endocrine disrupting chemicals, and that the work environment is heavily contaminated with dust and fumes. Consequently, plastics workers have a body burden that far exceeds that found in the general public. The nature of these exposures in the plastics industry places women at disproportionate risk, underlining the importance of gender.

A parallel epidemiological study of 1,005 women workers and 1,146 controls showed a five-fold elevated risk of premenopausal breast cancer among women in two occupations: the manufacture of automotive plastics and food processing (Brophy et al., 2012). It should be noted that this five-fold elevated risk is in addition to an escalating risk of breast cancer in the general population (Blue Green Alliance, 2013).

DeMatteo et al. point out that workers in the plastics industry are exposed to a “multitude of toxic chemicals used in plastics production, including styrene, acrylonitrile, vinyl chloride, phthalates, bisphenol-A (BPA), brominated flame retardants, heavy metals, solvents and other complex chemical mixtures.” This is of major concern as:

> . . . occupational exposures to chemicals used in the plastics industry may contribute to the development of breast cancer and reproductive problems, because they either act as mammary carcinogens or disrupt the normal functioning of the body’s endocrine system, or both. A recent study found that most plastic products release estrogenic chemicals [Yang, EHP, 2011]. Such endocrine-disrupting chemicals (EDCs) as phthalates, brominated flame retardants, and BPA are ubiquitous in the plastics work environment.

DeMatteo et al., provide considerable detail on the major processes involved in both polymer and plastic product manufacturing, and the documented occupational routes of exposure to unreacted monomers, processing chemicals, and plastics additives during various manufacturing processes. The authors' literature review found evidence that plastics processing workers consistently had higher body burdens of acrylonitrile, styrene, phthalates and BPA than the general population. Their research found that:

> . . . [I]t is generally accepted that the plastics processing work environment is potentially contaminated by residual monomers, polymers, and various additives, including plasticizers, stabilizers, pigments/colorants, flame retardants, activators, lubricants, and fillers, as well as solvents, paints, and finishing agents used in the decorating process. Some of these substances are mutagenic and known to cause cancer in humans, some are suspected of causing cancer, and some have been identified as endocrine-disrupting chemicals that may promote cancer.

DeMatteo et al., point out that while monomers are generally used up during polymerization, residual monomers including vinyl chloride, styrene, acrylonitrile, BPA, formaldehyde, butadiene, ethylene and urethane can still be released during resin production or thermal processing. In addition to the monomers, plastics processing involves the use of the solvents benzene, methyl ethyl ketone (MEK), and toluene, which are all mammary carcinogens. The manufacture of plastic products includes the use of a vast array of potential additives, including phthalates, heavy metals (lead, cadmium, tin, barium, and antimony) as pigments and stabilizers, and polybrominated diphenyl ethers (PBDEs), all of which are CoHCs.

DeMatteo et al. conclude with the following statements:

> . . . [t]hrough a review of the known health effects of substances used in the plastics industry we were able to ascertain that workers are chronically exposed to substances that are potential carcinogens and endocrine disruptors. This situation is aggravated by the fact that workers are exposed to complex mixtures of hazardous substances that may have additive and/or synergistic effects . . . we found through our review of the literature that workers carry a body burden of plastics-related contaminants that far exceeds those documented in the general public . . . existing epidemiologic and biological evidence indicates that women in the plastics industry are developing breast cancer and experiencing reproductive problems at elevated rates as a result of these workplace exposures.
>
> Finally, it has been demonstrated that many plastics-related substances are EDCs with adverse effects at very low levels. The ability of EDCs to disrupt the endocrine system at low levels lends biological plausibility to the link between workplace exposures and increased risk of breast cancer and reproductive problems for women working in the plastics industry.

The U.S. Environmental Protection Agency provides some indication of the sheer volume of chemicals to which communities in the U.S. are potentially exposed. An EPA report identified 38,265,753 million pounds of waste generated and disposed of both on-site and off-site by plastics and rubber facilities.

While workers are at the front line of exposure in manufacturing, local communities and environments are at the back end of exposure to the CoHCs used to manufacture plastics. The U.S. Environmental Protection Agency's (EPA's) Toxics Release Inventory (TRI) provides some indication of the sheer volume of chemicals to which communities in the United States are potentially exposed. A search via the U.S. EPA's TRI 2012 reporting data for the North American Industry Classification System (NAICS) 326, which encompasses Plastics and Rubber production, showed a reported 38,265,753 million pounds of waste generated and disposed of both on-site and off-site by reporting facilities. The results of the search includes many of the primary, intermediate, and monomer chemicals highlighted previously, as well as chemicals in the many classes of additives added to plastics in the process of making plastic products (U.S. EPA, 2014).

Exposure to CoHCs from Plastics during Usage and End of Life Management

There are many examples of plastic products that have been shown over time to contain chemicals that are detrimental to the health of consumers and the environment. Table 4 contains several well-known examples: BPA in baby and water bottles made from polycarbonate, DEHP in PVC IV bags, and brominated flame retardants (BFRs) in electronic products.

Recent books and articles continue to highlight consumer concerns around plastic products, including the 2011 book, *Plastic: A Toxic Love Story,* in which journalist Susan Freinkel follows the life cycles of eight common plastic products: the comb, a chair, the Frisbee, an IV bag, the disposable lighter, grocery bag, soda bottle, and credit card. Freinkel summarizes her key theme as follows:

> Plastic built the modern world. Where would we be without pacemakers, polyester, computers, cellphones, sneakers or chewing gum. . . . But a century into our love affair with plastic, we're starting to realize it's not such a healthy one. Plastics draw on dwindling fossil fuels, leach harmful chemicals, litter landscapes, and destroy marine life. And yet each year we use and consume more; we've produced as much plastic in the past decade as we did in the entire twentieth century. We're trapped in an unhealthy dependence—a toxic relationship.

Research continues to accumulate that highlights the hazards of exposure to products in our homes, particularly to children. For example, a May 2014 article in *Environmental Health Perspectives* linked prenatal exposure to flame retardants to lower IQs and greater hyperactivity at five years of age. A 10-fold increase in PBDE concentrations in early pregnancy was associated with a 4.5 point decrease in IQ, comparable to the well-documented exposure to lead in the environment (Chen, et. al, 2014). A February 2014 article in the Journal of Epidemiology and Community Health outlined the necessity for and challenges inherent in studying human exposure to food contact materials (FCM) as a

TABLE 4 Examples of Plastic Products and their Associated Chemical Hazards

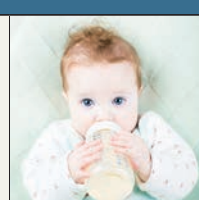
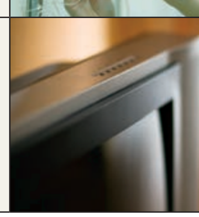
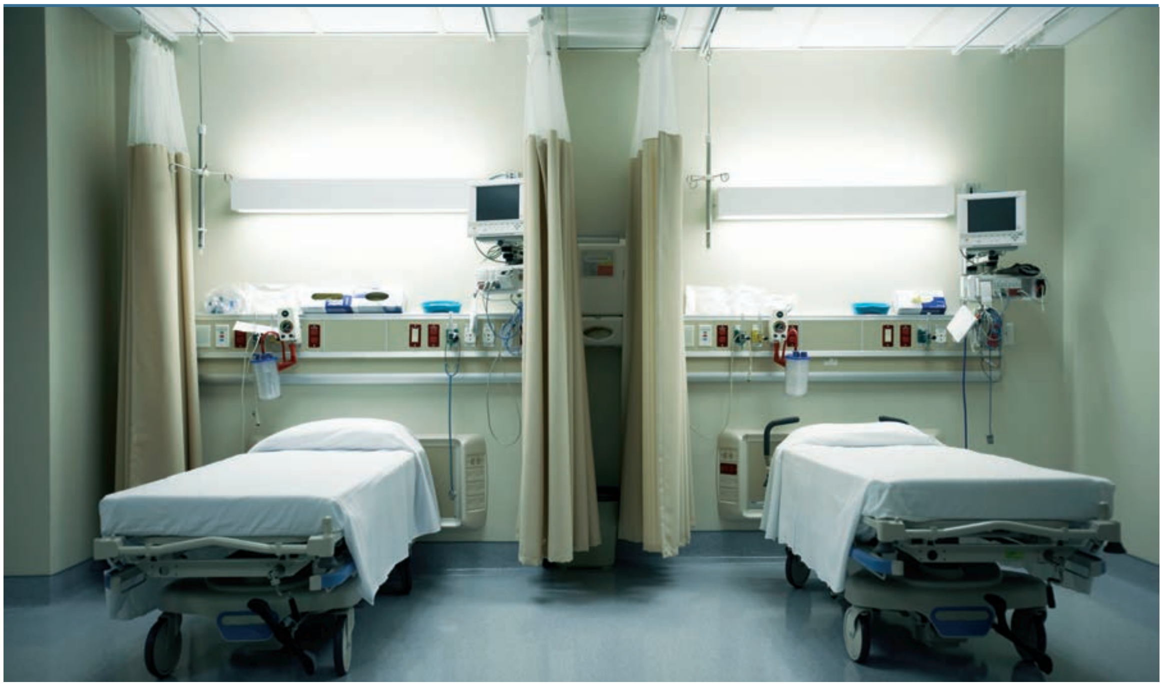
Plastic Product		Chemical Hazards
Baby bottles made from polycarbonate		Leaching of endocrine disruptor Bisphenol A (BPA)
Intravenous (IV) bags made from polyvinyl chloride (PVC)		• Leaching of endocrine disruptor and reproductive toxicant DEHP plasticizer • Use of carcinogen, vinyl chloride monomer (VCM) in manufacturing • Formation of carcinogenic dioxins during manufacture and end of life burning
Plastic housings for electronic products made from polystyrene with brominated flame retardants (BFRs)		Shedding of reproductive and developmental toxicant BFRs into household dust

Photo: © (top) Thinkstockphoto/FamVeld; (middle) © Thinkstockphoto/whitetag; (bottom) © Thinkstockphoto/agencyby



significant source of chemical food contamination. The authors state: "Most often FCMs are made of plastic or have a synthetic material in direct contact with the foodstuff. . . . Importantly, most FCMs are not inert. Chemicals contained in the FCM, such as monomers, additives, processing aids or reaction by-products, can diffuse into food" (Muncke, et al., 2014).

End of life concerns with chemicals in plastics emerge for all the various management options. For the reuse and recycling of plastics, the presence of "legacy" CoHCs will impede the reuse/recycle of plastic products as well as expose workers handling the materials to the CoHCs. For example, the persistent, bioaccumulative, and toxic flame retardant, pentabromodiphenyl ether (pentaBDE) in furniture foam, now creates a major barrier to the recycling of the foam; with similar issues happening with the recycling of electronic enclosures containing decaBDE. For the incineration of plastics, any heavy metals in the plastic, like lead or cadmium will either become airborne or will contaminate the fly ash that must be disposed of (or recycled). For other plastics with bromine or chlorine content there will be emissions of brominated and chlorinated dioxins and furans. Finally, if plastics are landfilled at end of life, chemicals can leach from the plastics, through the landfill and into neighboring groundwater.

These examples and other research highlight the need to reduce the hazards of plastic chemicals both in production and in products.

Leading Business Sectors Search for Safer Plastics

Current initiatives in the health care, electronics, apparel and footwear, and building products sectors highlight the drivers for incorporating safer chemistry in decisions on plastics and other materials, the attributes considered, and the methods that these systems use to assess and select safer plastics. These practices are driven by a range of motivations, such as:

- regulatory compliance
- marketplace advantage
- green certification
- government procurement specifications
- improvements in indoor air quality (e.g., for building products and furnishings)
- corporate commitment to actively avoid high hazard chemicals

The Sector Initiatives box (page 22) spotlights growing demands for plastics made without CoHCs in the health care, apparel and footwear, and building product sectors. These initiatives provide instructive examples of how organizations within three sectors are already trying to move their sector or company to safer plastics.

Photo: © Thinkstockphoto/Fuse

BOX 1 **Sector Initiatives to Reduce Chemicals of High Concern (CoHC) in Plastics**

Health Care

Initiative

Practice Greenhealth's Standardized Environmental Questions for Medical Products (PGH, 2011)

Drivers

To use purchasing practices to selectively choose medical products for hospitals and other healthcare facilities that are inherently safer for patients, workers, and the environment; and to increase demand for and supply of these products.

How the initiative addresses safer chemicals in plastics

A questionnaire for health care purchasers asks a series of questions related to chemicals in products being evaluated, with preferred responses. Questions address the presence of polyvinyl chloride (PVC), phthalates, bisphenol A (BPA), halogenated organic flame retardants, mercury, latex, and carcinogens and reproductive toxicants, as well as the generation of hazardous waste.

Example question

Is this product free of intentionally added Bisphenol A (BPA) or BPA derived plastics (such as polycarbonate plastic and resins)? (Yes/No) Preferred response is "yes."

Apparel & Footwear

Initiative

Nike's Materials Sustainability Index (MSI) (Nike, 2012)

Drivers

To provide product creation teams at Nike with a tool to select environmentally better materials.

How the initiative addresses safer chemicals in plastics

The Nike MSI scoring framework includes a chemistry score, which is calculated using an algorithm and data addressing "significant chemical substances" across the cradle-to-gate life cycle of a material. For polymers, significant chemical substances are those present in principal reactions, including known catalysts, from the raw material source through polymer formation. The chemistry score combines human health hazard evaluations for carcinogenicity, acute toxicity, chronic toxicity, and combined reproductive toxicity, and endocrine disruption with assumptions about potential exposures during the life cycle. Eco-toxicity is not considered. For components, such as molded parts, foams and buttons, the assessment spans from raw materials to the creation of the basic material (called Phase 1, e.g., polymer pellets) and the additional processes that transform the basic material into the materials that are shipped to an assembly facility (called Phase 2, e.g., processing pellets into a foam).

Nike has made the MSI available to other companies and to the general public through the Sustainable Apparel Coalition.

Building Products

Initiative

Perkins+Will Precautionary List (P+W, 2014)

Drivers

The goal of this program is to provide information to the building industry on chemicals of concern in building materials and safer alternatives.

How the initiative addresses safer chemicals in plastics

The Perkins+Will Precautionary List includes a total of 25 substances, groups of substances or materials commonly found in building products that are listed by government agencies or identified in scientific research as having negative health impacts. The list includes bisphenol A (BPA), halogenated and brominated flame retardants, phthalates, polyurethane foam, and polyvinyl chloride (PVC). Perkins+Will's public Transparency website contains the Precautionary List of chemicals, detailed information on the health effects of the substances, building products that typically contain substances (by CSI MasterFormat™ division and section), as well as alternatives.