

Developing the economic engine for
sustained reduction and elimination of
marine plastics by investing in bio-benign
materials, innovative packaging design and
manufacturing

Innovation landscape

October, 2016

**Think
Beyond**
PLASTIC

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Abbreviations

ABS	Acrylonitrile butadiene styrene
AC	Acrylic
ACC	American Chemistry Council
BDE	Bromodiphenyl ether
BPA	Bisphenol A
CDC	Centers for Disease Control and Prevention
CE	Central Europe
CEO	Chief Executive Officer
CIS	Commonwealth of Independent States
COSHH	Control of Substances Hazardous to Health
CSO	Combined Sewer Outfall
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
DEHP	Di-(2-ethylhexyl) Phthalate
DNA	Deoxyribonucleic acid
EEC	European Economic Community
EDC	Endocrine Disrupting Chemical
EfW	Energy from Waste
EMF	Ellen MacArthur Foundation
EPA	Environmental Protection Agency
EU	European Union
FAO	Food and Agriculture Organization
FCB	Full Cycle Bioplastics
Fs	Furans
GEB	Global Environmental Benefits
GEF	Global Environmental Facility
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHG	Greenhouse Gas
GMO	Genetically Modified Organisms
HDPE	High density polypropylene
ILO	International Labor Organization
ISWA	International Solid Waste Association
LCA	Lifecycle Analysis
LDC	Less developed Countries
LDPE	Low Density Polypropylene
MSW	Municipal Solid Waste
MVP	Minimum Viable Product
NAFTA	North American Free Trade Agreement
NGO	Non Governmental Organization
NP	Nonylphenol
OECD	Organization for Economic Co-operation and Development
PBDE	Polybrominated diphenyl ether
PCB	Polychlorinated biphenyls
PCCD	Poly-Chlorinated dibenzo-dioxins
PCCP	Personal Care and Cosmetic Products

PCP	Personal Care Products
PE	Poly Ethylene
PES	Polyester
PET	Polyethylene terephthalate
PHA	Polycyclic aromatic hydrocarbon
PMMA	Polymethyl methacrylate
POP	Persistent Organic Pollutants
rPET	recovered Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinyl chloride
RAPEX	Rapid Exchange of Information System
RIC	Resin Identification Code
STAP	Science and technology Advisory Panel
SIDS	Small Island Developing States
TPS	Thermoplastic starch
UK	United Kingdom
UN	United Nations
UNEA	United Nations Environmental Assembly
UNEP	United Nations Environment Programme
USA	United States of America
WE	Western Europe

Executive Summary

This paper was produced at the request of the Scientific Technical and Advisory Panel (STAP) for the Global Environment Facility (GEF), in an effort to showcase how Green Chemistry innovations can address the global challenge of plastic pollution. The terms of reference for this paper were derived under the STAP Work Programme for GEF-6, as the first of a potential compendium of Green Chemistry applications to showcase to the GEF possible areas of future pilot investment; in this instance, in the area of plastic alternatives to combat the ubiquitous plastic pollution and associated chemical exposure problems the modern world is facing.

The GEF CEO has consistently called for enhanced incorporation of innovation into the GEF Portfolio. The STAP, as the arm of the GEF corporate infrastructure responsible for scientific and technical advice, recognized that much innovation lies in academia, but also in private sector, and recognized many critical partners operating at the nexus of innovation and plastic pollution with focus on materials, manufacturing and product design. As the STAP seeks to provide the international context and construct surrounding sustainable production and consumption, it proposed that the GEF be the mechanism by which such innovations might be piloted to generate Global Environment Benefits (GEBs). Dr. Ricardo Barra, University of Concepcion, Chile, and the STAP Panel Member on Chemicals, leads this work within the STAP.

This advisory presents some of the findings of a global eco-system emerging at the nexus of innovation, entrepreneurship and plastic pollution. The ecosystem includes public and private entities in business, science, policy, academia, investment, and technology commercialization, many of whom have contributed to this advisory through their work with entrepreneurs, investors, impact investors, philanthropists, philanthropreneurs, business executives and thought leaders.

This paper presents emerging innovations that have the greatest potential to reduce the global problem of marine plastics, with minimum negative economic and environmental externalities along the way. The innovations are examined through the lens of green chemistry¹, economic, and business benefits, which naturally eliminates some innovations and gives preference to others; a holistic, systemic view of the entire problem which starts upstream, long before plastic becomes trash.

The innovation landscape is dynamic and evolves rapidly as long as there is consumer demand, adequate investment, and identifiable target markets. The innovations presented here are only as accurate as of the date of writing. Therefore, this paper can provide the GEF partnership and any other readers with just a general direction and path to economic and environmental viability, and suggest a decision matrix for future investments.

Plastic has had multiple beneficial impacts on society that are well understood and well documented. From the first synthetic phenol-formaldehyde based plastic, made in 1907 by Leo Baekeland, to the present day, plastic has proven to be immensely valuable in protecting natural resources such as cork, leather, bone etc, and very versatile. This versatility has resulted in rapid industry growth and job

¹ Described later in this document

creation, supporting major socio-economic trends and societal shifts, and providing livelihoods to millions worldwide. Modern society without plastic is difficult to imagine.

Three key characteristics of society's reliance on plastic are worth mentioning:

- Rapid growth across many sectors of socioeconomic activity;
- Job creation;
- Reliance on low-cost fossil fuels: natural gas, coal and petroleum

Today, products made from plastic can be found in almost any sphere of socioeconomic activity, from medical services, to construction, aerospace, food services, consumer products and goods, and beyond. Plastic products are lightweight, yet they are strong, long-lasting, pliable, and versatile – all attractive qualities to consumers and businesses alike. As innovations in chemistry and plastic production produced new applications, global plastic production has enjoyed rapid growth and has increased 20-fold since the 60-ies (McKinsey *et al.*: 2016). The plastic industry projects this growth to continue, with production expected to reach almost 1200 MT by 2050. Most of this growth is expected to come from the packaging sector and particularly from single-use and disposable plastic items (Plastics Europe: 2016).

Currently, plastic production represents a market of approximately US\$500 Billion (Plastics Europe 2016) and employs globally over 6,000,000 people (Plastics Industry Trade Association 2015). Protecting these livelihoods is an essential and important goal for the industry and underlies efforts to maintain and grow the use of conventional² plastic as the material of choice across a multiplicity of uses.

Finally, the wave of recent innovation in the production of natural gas and the oil glut are expected to make producing conventional plastic even more cost-effective in the years to come.

In the last 20 years, society has come to realize that this unprecedented growth of reliance on plastic has been accompanied by externalities, the costs of which are borne not by industry, but by governments, tax payers and global citizenry, and the environment. These externalities include fossil fuel consumption, depletion of natural resources, threats to environmental and human health, and related growing economic damages not previously considered. If current trends hold, by 2050 the plastics industry may surpass the global airline industry in fossil fuel consumption (McKinsey *et al.* 2016).

Plastic pollution has become a crisis on the scale of “global threat”, comparable to global climate change, food security and water scarcity. Moved to address this crisis, society has leaned on traditional management methods, but the ubiquitous spread of plastic pollution in our land, seas, air and even biota has demonstrated that these measures are not adequate. New data about plastics and associated toxicity has scientists calling for plastic trash to be classified as “hazardous material” (Rochman *et al.* 2013) that creates a problem of a more substantial magnitude than simply dealing with trash.

Recycling, while generally necessary and effective for other materials, has not proven a successful match to the exponential growth of disposable plastic waste. Recycling rates worldwide have trailed at

² Plastic derive from fossil fuels such as petroleum and natural gas.

about 14% (McKinsey *et al.*: 2016), leaving behind vast amounts of uncollected plastic trash. Since plastic is long-lasting, these accumulations do not reduce in size, except in marine environments where they break down into small and highly toxic particles known as *microplastics*.

Culture change, while important, takes time –the disposable trend took almost 50 years of consistent and strong consumer marketing to become deeply embedded in the modern developed society (*Life Magazine* 1955). The current movement towards reusability, by contrast, is not nearly as strong or powerful partially because it is not driven by business interest.

Policies and bans restricting certain disposable plastics or *plastisizer* chemicals are very effective, yet resource-intensive and typically met with resistance by business and often, even amongst consumers. More importantly, policies restricting products with valuable commercial use can only be effective when there are viable commercial alternatives.

Waste to value innovation (such as waste-to-energy) is a growing interest to many middle-income and developing economies³ who view it as an opportunity to quickly handle the pollution problem and derive economic benefits in the process. In some cases, such as in Jamaica, where plastic trash is mixed with cement, this is an opportunity to create jobs and expand the construction industry. Yet mostly, energy produced from plastic waste comes with a high environmental price tag (Blue Ridge Environmental Defense League 2009), it is subject to market volatility of crude oil prices, and creates a perverse incentive to generate more plastic waste. Waste-to-energy installations in Europe⁴ have turned to importing waste to continue to generate the energy generated by the vast incinerators it has built, as countries have moved towards zero-waste and towards reducing disposable plastic waste.⁵

The circular economy approach is the latest and most visionary attempt to address plastic packaging. With full understanding that the current linear approach of *use-discard* presents an enormous brand challenge to industry and economic burden on society, the Ellen MacArthur Foundation presented a model for plastic packaging “after-life.” Assuming no change in material and consumption patterns of current conventional plastics, and no material innovation, the circular approach will likely result in a search for new ways to reuse plastic waste, an ever increasing size of the circle, and a pathway to more harmful releases of chemicals into the environment and biota. The circular approach has a great promise for success if it incorporates substantial decoupling from fossil fuel feedstocks (higher than its current target of 2%) and a strong focus on collection and reuse of the material that is already present in the environment.

³As observed by Think Beyond Plastic’s field work in Central America, South America and Africa

⁴Austria, Belgium, Germany, Denmark, the Netherlands and Sweden landfill 3% of municipal waste have long counted on waste to energy to manage their landfill costs

⁵In a well-known example, Norway pays Sweden for their waste and Sweden also gets electricity and heat. But dioxins in the ashes of the waste and the heavy metals byproduct are a serious environmental pollutant and concern. <http://www.gmanetwork.com/news/story/280129/scitech/science/swedenimportstrashforenergy>

There appears to be no lack of good will and an urgent desire to act since the mounting economic costs of plastic pollution are significant (UNEP 2014), and the impacts on human and other biota are well documented. What makes the plastic pollution problem so difficult to solve are the contradicting interests of the stakeholders - industry, entrepreneurs, investors, civil society, and consumer advocacy groups who share diverse and often conflicting priorities:

- **The plastics and chemical industries** must protect revenues, jobs, and business growth, therefore they are inclined to protect current investments in infrastructure, support interventions that do not pose risks to these investments, and place the burden for end-of-life management of plastics on governments or society.;
- **Businesses using plastic packaging** depend on the price-performance properties of the current material, in order to protect their cost structure and business and consumer advantages. They might be willing to experiment with alternate materials only if there is a clear cost benefit or brand advantage⁶;
- **The environmental community** seeks to protect eco-systems, human health and other biota from the impacts of plastic production such as extraction, manufacturing, and end-of-life. They see as a clear path in reducing consumption of disposable plastics, and in a culture of reuse, often consumer costs incompletely assessed or considered;
- **Consumers** value the convenience of disposability and the low price of plastic items, but are increasingly aware of the environmental impacts and the toxic impacts on health. Some might be willing to accept higher prices, for alternative materials but this is not the norm;
- **The investment community** is interested in investments in alternatives as they observe the emergence of consumer demand, but are typically risk-averse, especially when the alternatives are in early-stage and represent platform technologies;
- **The impact investment community** wants clear benchmarks for social, environmental and economic impacts – but the market is too young to demonstrate them yet. Notable exceptions are businesses that encourage PET recycling to produce “responsible fabric” and plastic threads, while creating jobs and economic opportunities for marginalized communities;
- **The entrepreneur community** wants to see investments in their innovations, but also needs access to material innovation labs, and full-scale manufacturing capacity to test their pilot manufacturing.

Taking these diverse needs into consideration, if a new material is created, it must have: (a) the exact or better economic and performance properties of conventional plastic; (b) no toxic impacts of extraction, manufacturing, and end-of-life on the biota; (c) demonstrable benefits for the emerging impact investment community; and (d) clear metrics for success.

No such single material (or solution) currently exists.

What does exist is a vibrant innovative and entrepreneurial community that is generating a large portfolio of innovations, and start-ups that can be accelerated towards that goal. These innovators and

⁶ Examples of companies with this brand advantage include Lego, HP, Dell, etc.

entrepreneurs are creating the next generation of materials that are bio-benign, sustainably produced and manufactured, and have the capacity to transform the plastic pollution problem. These materials might not be able to address all of the performance requirements for all plastics, but might be great at targeting some. The loss in some features might be an acceptable tradeoff for their environmental benefits. This approach works well with recycled paper whose visible color and texture differences set it apart from virgin paper, and yet clearly demonstrate its environmentally-friendly origin. There are many applications for plastic where tradeoffs in features and performance are possible and desirable.

What the innovation and entrepreneurial community needs is:

- a good understanding and focus on the “hot spots” of pollution⁷, i.e. the high-value urgent problems and the acceptable price-performance and feature trade-offs;
- a necessary investment level including fully equipped material innovation labs, infrastructure and pilot manufacturing facilities;
- government support to incentivize R&D, de-risking early investments, offset even partially investments in benign plastic alternatives;
- collaboration and guidance by environmental and consumer advocacy organizations, and most importantly,
- collaboration and feedback by the largest customers – the plastic and chemical industry, and major consumer brands using plastic packaging.

In other words, innovation alone is not enough.

Each of the stakeholders have demonstrated the will to work towards a solution that is economically and environmentally feasible, as the continued impact of the “business-as-usual” scenario on the eco-systems and human health is clearly untenable.

The time has arrived to join efforts across public and private sector to disrupt the status-quo and to deliver on the promise of the circular economy, by creating the next generation of bio-polymers that can replace plastic waste with cost effective, completely biodegradable, non-toxic products, derived from bio-benign feedstocks that do not challenge the global food security or threaten fragile eco-resources. The waste stream can become the feedstock for valuable products generating income and livelihoods for entire communities.

The best opportunity for such disruption is presented by investments in green chemistry innovation.

Similarly to investing in clean energy, green chemistry innovations are investments in the future, not in cleaning up the past. They have the potential to enable new businesses, to create new jobs, and to open up new markets and new opportunities. These opportunities could revitalize dormant or suffering markets, or take over from legacy industries. These are jobs that will require training of individuals and create opportunities for future growth. Instead of solely investing in trash management, these investments will enable the creation new economy based on the multiple beneficial impacts of green chemistry innovation, a *new plastics* economy.

⁷ See discussion on “hot spots” later in this paper

To achieve long-term global environmental benefits, global organizations such as the GEF can help by de-risking early stage investments in such disruptive innovations with demonstrated environmental potential; and by driving international policies that support a circular economy and provide innovation incentives, modeling on successful global initiatives. This is not just a case for individual innovations, but a case for building and growing the entire innovation eco-system.

About Plastic

Plastics are some of the most important materials for our society, as evidenced by their widespread usage in agriculture, food packaging, clothes, shelter, communication, transportation, construction, health care and leisure industries.

Plastics help reduce food waste by keeping products fresh longer; allow for the manufacture of life-saving healthcare equipment; reduce packaging mass compared with other materials; improve transportation efficiency; and might even have some potential for use in renewable energy technologies.

The versatility of plastic has resulted in rapid industry growth and job creation, whilst reducing the depletion of natural materials (silk, wood, cork, leather, ivory and many others) and supporting major socio-economic trends. The benefits of plastic to society are numerous, and modern life without plastic is difficult to imagine.

Brief History of Plastic Innovation

The development of plastics is believed to have started around 1860, when Phelan and Collander, a U.S. pool and billiard ball company, offered a prize of US\$10,000 to the person who could design the best substitute for natural ivory. One of the entrants (although not the winner) was John Wesley Hyatt, who developed a *cellulose derivative* for the contest. His product was later patented under the name “Celluloid” and was quite successful commercially, being used in the manufacture of products ranging from dental plates to men’s collars.

Over the next few decades, more and more plastics were introduced, including some modified natural polymers like *rayon*, made from cellulose products. Shortly after the turn of the century, Leo Hendrik Baekeland, a Belgian-American chemist, developed the first completely synthetic plastic which he sold under the name “Bakelite”.

In 1920, a major breakthrough occurred in the development of plastic materials. A German chemist, Hermann Staudinger, hypothesized that plastics were made up of very large molecules held together by strong chemical bonds. This spurred an increase in research in the field of plastics. Many new plastic products were designed during the 1920s and 1930s, including *nylon*, *methylmethacrylate* (also known as “Lucite” or “Plexiglas”), and *polytetrafluoroethylene*, which was marketed as “Teflon” in 1950.

Many countries were struck by a shortage of natural raw materials during World War II. With Japan’s entry into the war, the United States, in particular, was no longer able to import natural rubber, silk and many metals from most Far Eastern countries. Instead, the Americans turned to the plastics industry. Nylon was used in many fabrics, polyesters were used in the manufacturing of armor and other war materials, and an increase in the production synthetic rubbers occurred.

Advances in the plastics industry continued after the end of the war. Plastics were used in place of metal in such things as machinery and safety helmets, and even in certain high-temperature devices. Karl Ziegler, a German chemist, developed *polyethylene* in 1953, and the following year Giulio Natta, an Italian chemist, developed *polypropylene*. These are two of today's most commonly used plastics.

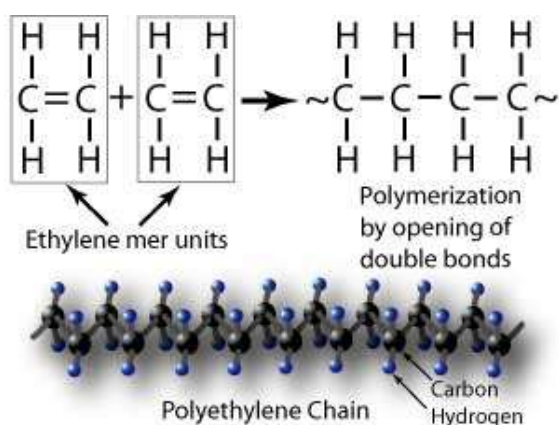
Today, products made of plastic can be found in almost any sphere of socioeconomic activity, from medical services, to construction, aerospace, food services, consumer products and goods, and beyond, often replacing materials such as glass, wood and metal. Plastic products are lightweight, long-lasting, pliable, versatile, yet strong – all attractive qualities to those who would employ them. By 2009, plastic packaging accounted for almost 30 percent of packaging sales (McKinsey *et al.* 2016). With the push by U.S. federal mileage standards to reduce the weight of vehicles (EPA 2012), the American automobile industry has been a champion of increased use of plastics, such that plastics make up about 10 percent by weight (50 percent by volume) of a typical U.S. vehicle today (ACC 2015), representing 153 kg of plastic per vehicle. In contrast, in 1960, less than 9kg of plastic were used in cars. Plastics now often replace metals in bumpers and door panels as well as in engine components (ACC 2015).

Initially, all early plastics were derived from renewable resources; but in 1931 DuPont came out with the first petroleum-based polymer, named *neoprene*. From that point on, the feedstock for plastic production was non-renewable fossil fuel and natural gas, and the manufacturing rates closely matched the economics of oil and natural gas.

Today between 4 and 6 percent of the global annual petroleum consumption is used to make plastic, and another 4 percent is used to power plastic manufacturing processes (Gourmelon 2015, McKinsey 2016).

Chemistry

Plastics are polymers. A polymer is a substance made of many repeating units. The word polymer comes from two Greek words: poly, meaning many, and meros, meaning parts or units. A polymer can be



thought of as a chain in which each link is the monomer (single unit). There are two types of plastics, *thermoset* and *thermoplastic*.

A *thermoset* is a polymer that solidifies or “sets” irreversibly when heated or cured. Similar to the relationship between a raw and a cooked egg, a cooked egg cannot revert back to its original form once heated, and a thermoset polymer can’t be softened once “set”. Thermosets are valued for their durability and strength and are used extensively in automobiles and construction including applications such as adhesives, inks, and coatings. The most common thermoset is the rubber tire. Others include polyurethanes, unsaturated polyesters, epoxies, and phenol formaldehyde.

Figure 1. Polyethylene Chain

polyesters, epoxies, and phenol formaldehyde.

A *thermoplastic* is a polymer in which the molecules are held together by weak secondary bonding forces that soften when exposed to heat and return to its original condition when cooled back down to room temperature. When a thermoplastic is softened by heat, it can then be shaped by extrusion, molding, or pressing. Thermoplastics offer versatility and a wide range of applications. Examples of thermoplastics include polyethylene, polypropylene, and polyvinyl chloride. They are commonly used in food packaging because they can be rapidly and economically formed into any shape needed to fulfill the packaging function. Examples include milk jugs and carbonated soft drink bottles.

The formation of the repeat units for thermoplastics usually begins with the formation of small carbon-based molecules that can be combined to form monomers. The monomers, in turn, are joined together by chemical polymerization mechanisms to form polymers. The raw material formation begins by separating the hydrocarbon chemicals from petroleum or coal into streams of chemicals. Some are then processed in a “cracking process.” Here, in the presence of a catalyst, the long-chained hydrocarbons are cracked into shorter units such as ethylene, propylene, butane, and others. All of these monomers contain double bonds between carbon atoms such that the carbon atoms can subsequently react to form polymers. Other raw material chemicals are isolated from petroleum, such as benzene and xylenes. These chemicals react with others to form the monomers for polystyrene, nylons, and polyesters.

Monomers are then chemically bonded into chains called polymers. There are two basic mechanisms for polymerization: addition reactions and condensation reactions. For addition reactions a special catalyst is added, frequently a peroxide that causes one monomer to link to the next. Catalysts do not cause reactions to occur, but cause the reactions to happen more rapidly. Addition polymerization, used for polyethylene, polystyrene and polyvinyl chloride, among others, creates no byproducts. The second polymerization mechanism, condensation polymerization, uses catalysts to have all monomers react with any adjacent monomer. The reaction results in two monomers forming dimers (two unit cells) plus a byproduct. Dimers can combine to form tetramers (four unit cells) and so on. For condensation polymerization the byproducts must be removed for the chemical reaction to produce useful products. Polyesters and nylons are made by condensation polymerization.

Different combinations of monomers can yield plastic resins with different properties and characteristics. When more than one monomer is used, the polymer is called a copolymer. Laundry detergent bottles are an example of copolymer HDPE. Combinations of monomers produce copolymers with further property variations.

Plastic Additives

When plastic polymers are initially manufactured, they may or may not have the desired properties for a commercial product. The inclusion of additives may impart specific desirable properties, suitable for commercial applications. Some polymers incorporate additives during manufacturing while others include additives during processing into their final products. Additives are incorporated into polymers to alter and improve basic mechanical, physical or chemical properties. They are also used to protect the polymer from the degrading effects of light, heat, or bacteria; to change such polymer processing properties such as melt flow; to provide product color or transparency; and to provide special characteristics such as improved surface appearance, reduced friction, increased flexibility and flame retardant qualities.

Some frequently used plastic additives include:

- Antioxidants for plastic processing and outdoor applications where weather resistance is needed. Typical antioxidants are organophosphates and butylated hydroxytoluene.
- Colorants for colored plastic parts or products. Colorants include a variety of inorganic and organic dyes and pigments (e.g., titanium dioxide).
- Foaming or blowing agents for expanded polymers such as polystyrene building board, insulation, food packaging and polyurethane carpet underlayment and spray foam insulation. Typical foaming agents are isocyanate for expanded polyurethane.
- Plasticizers that increase flexibility and fluidity of the polymer. Typical plasticizers are phthalate esters used in polyvinyl chloride products.
- Lubricants that improve melt flow or to reduce adhesion of the molten plastic to the metal surface. Typical lubricants are calcium, zinc, and lead stearates, petroleum and polyethylene waxes.
- Anti-statics to reduce dust collection by static electricity attraction. Typical anti-statics are amines, quaternary ammonium compounds, organic phosphates, and polyoxyethylene glycol esters.
- Antimicrobials used to inhibit the growth of bacteria, fungus, mold, or mildew. Typical antimicrobial additives are arsenic-based materials such as oxybisphenox arsine, isothiazalone biocides, and triclosan (chlorinated diphenyl ether).
- Flame retardants and brominated flame retardants to improve the safety of a variety of plastic products. Typical flame retardants are organophosphate compounds.

These additives are essential for the production of plastic products, as they provide the qualities that make these products valuable and convenient. At the same time, many of these additives are compounds that are known and documented carcinogens and endocrine disruptors with long-lasting impacts on public health, as discussed later in this paper.

Because polymerization of monomers is rarely complete and additives are not chemically bonded to the polymeric structure, these chemicals can leach from plastic products. This process and the adverse health effects associated with leaching of endocrine disruptors and carcinogens in particular are described in more detail in the section on Human Health Impacts.

Most Common Plastic Manufacturing Processes

Plastic manufacturing involves several processes which have documented impacts on workers (DeMatteo 2011). Plastic resin enters the workplace in the form of pellets, powders, granules, liquids or syrups. During the handling of the bulk product by opening, pouring, scooping, and subsequent stirring, mixing and grinding, sanding and buffering, the dust and fumes can lead to air contamination through a variety of methods:

Resin Preparation is the first step in plastic production. The resin formulation and additives are adapted to the final desired product (e.g. PVC, PP, PT or others). *If the process is manual and in batches, the probability of exposure via direct contact or inhalation of possible hazardous substances (vapor, dusts, liquids) to the workers can be high.*

Extrusion—Plastic pellets or granules are extruded to thin layers as used for plastic films and bags. Extrusion is done with hot plastics and in the open with venting and poses a *high possibility of exposure to the workers*.

Injection molding—Plastic pellets or granules are injected into a mold. Injection molding is used for producing butter tubs, yogurt containers, closures, and fittings. This process is an enclosed thermal procedure, but the venting and melt degassing *pose a medium possibility of exposure to the workers*.

Blow molding—Blow molding is a process used to make, for example, carbonate soft drink bottles. The process of blow molding is in conjunction with extrusion or injection molding. The blow molding (enclosed thermal) process as such, *poses a medium possibility of exposure to the workers*.

Calendering molding—This process is used to form sheets and coatings. *Workers can be highly exposed to hazardous substances*, due to the open thermal process used for large surfaces.

The Unintended Consequences of Plastic Production & Consumption

Explosive Growth of Plastic Production

From 1.5M tons in 1957 to 311M tons in 2014 (McKinsey *et al.* 2016), global plastic production has increased by almost 20% annually (Plastics Europe 2016). This strong growth is projected to continue, enabled by the generally dropping commodities prices for natural gas and petroleum, and reliance on plastic in almost every aspect of the economy.

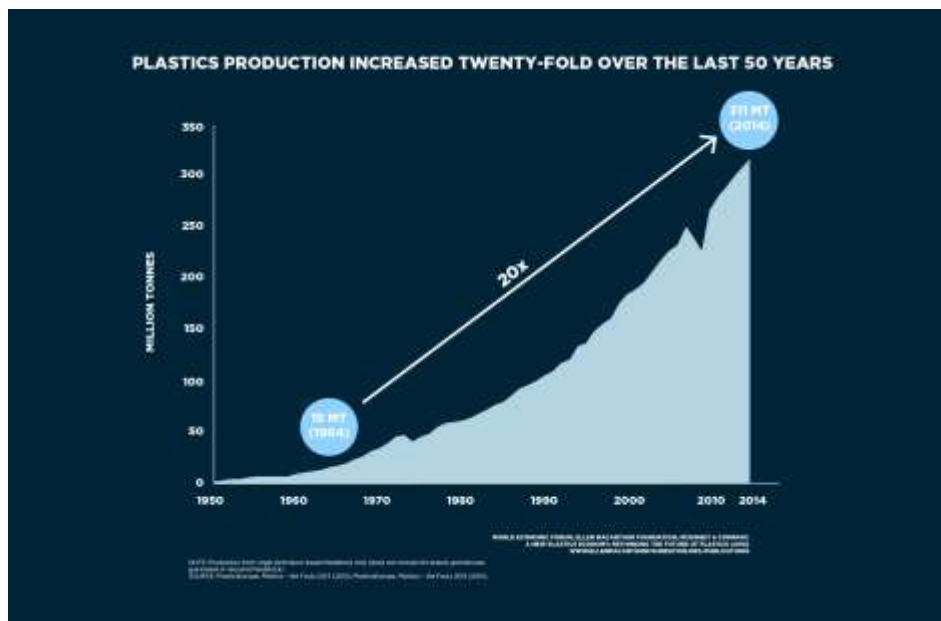


Figure 2. Plastic production increase 1957-2014 (McKinsey *et al.* 2016)

One of the fastest growing segments of plastic production is plastic packaging, the market's largest sector representing over 40% of the total volume (McKinsey *et al.* 2016). Not coincidentally, disposable

plastic packaging is the greatest contributor to plastic pollution as witnessed by the itemization of plastic trash by multiple environmental organizations including Ocean Conservancy (2015), Heal the Bay (2016) and others.

Between 2000 and 2015, the share of plastic packaging as a share of global packaging volumes has increased from 17% to 39.6%, driven by a strong growth in the global plastic packaging market (Plastics Europe 2016). Plastic packaging volumes are expected to continue their strong growth, doubling within 15 years and more than quadrupling by 2050 –greater than the entire plastics industry today (McKinsey 2016).

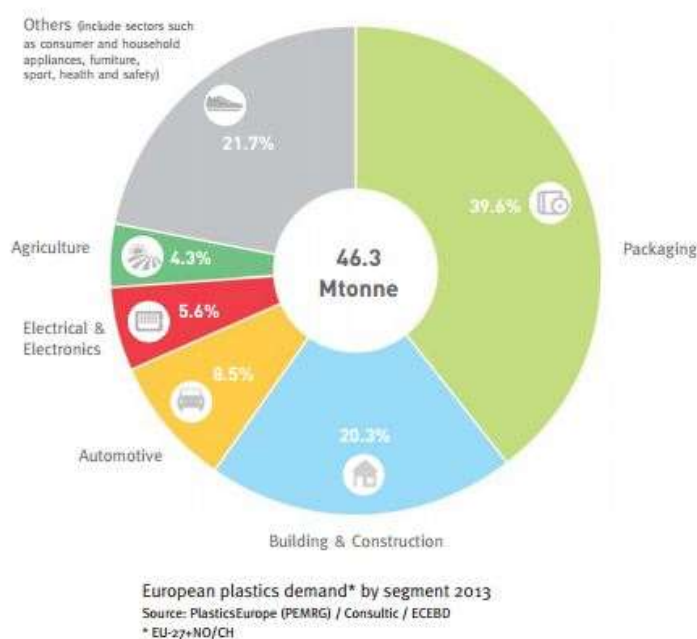


Figure 3 Plastic production by sector in Europe

In Europe, for example, packaging applications are the largest application sector for the plastics industry and represent 39.6% of the total plastics demand.

Building and construction is the second largest application sector with 20.3% of the total demand.

Automotive is the third largest sector with a share of 8.5% of the total demand. Electrical and electronic applications represent 5.6% of the plastics demand and are closely followed by agricultural applications which have a share of 4.3%. Other application sectors such as appliances, household and consumer products, furniture and medical products comprise a total of 21.7% of the European plastics demand.

These numbers are consistent with the global market share numbers, although no simple comprehensive source of similar data has been identified for the US and rest of world.

The rapid consumption of disposable plastic combined with inadequate lifecycle management has resulted in both visible and invisible accumulations of plastic trash around the globe (Leslie 2015, SEA 2010). These accumulations have been observed and reported by the science community and the public

for decades, with heavy focus, thus far, on the marine environment. Some of the original reporting about marine plastics came from the travels to the Midway Islands, the studies of Woods Hole Institute (SEA 2010) which were then followed with a thorough study on plastic pollution in the ocean by Jenna Jambeck (2015) and her research team⁸. Less evident in the literature is a study of the impacts of plastic pollution on soils and lands (Zalasiewicz *et al.* 2016). As early as 2012, The Smithsonian magazine has published reports about plastic pollution in the Antarctica (Stromberg 2012).

Attendant to the recognition of the existence of global accumulations of plastic, research has increasingly turned to the toxicological and biochemical impacts of the exposure of biota to plastic in the environment, as well as risks to human health from intended use.

Environmental Impacts

Land-based plastic pollution

Plastic accumulations on land are documented through the thousands of images of plastic pollution in communities on every continent and through the work of hundreds of NGOs on an international, national and regional level. However, there is little to no peer reviewed literature to explore the impacts of degrading plastics on soil and terrestrial ecosystems. This is a hiatus in research that is currently being eclipsed by the focus on marine impacts. Although the toxicological studies on plastics in terrestrial ecosystems are not yet evident in the literature, plastics have been noted as a geological marker to the Anthropocene (Zalasiewicz *et al.* 2016), and it has been noted that plastic is abundant in the environment as macroscopic fragments and is ubiquitous as microplastic particles, dispersed by both biological and physical processes. Zalasiewicz *et al.* (2016) opine that “...*plastics are already widely dispersed in sedimentary deposits, and their amount seems likely to grow several-fold over the next few decades. They will continue to be input into the sea over coming millennia, [even] as temporary stores—landfill sites— are eroded.*”

New data from experts in agriculture such as Southern Waste Information Exchange estimates that U.S. agriculture alone uses about a Billion pounds (.45 Billion Kg) of plastic a year. This includes films used for mulch, greenhouse covers, bale wrapping, tubing and pipes. It also includes nursery containers, pesticide containers, silage bags, storage covers, twine and more. Farmers in cooler regions use plastic to enhance warmth, while in the southern hemisphere, farmers use plastic to cool soil and plants.

Worldwide, the agricultural plastic film market alone was estimated to be worth US \$5.87 Billion in 2012 (Transparency Market Research 2013).

China is estimated to be the world’s largest consumer of agricultural plastic films, using about 60 percent of all such plastic (Liu EK, 2014).

Marine Plastics

Plastic accumulations in the ocean have been documented both in the media and in academic studies (Jambeck *et al.* 2015, Law *et al.* 2010, Barnes *et al.* 2009). The land-based and sea-based sources have also been studied and reported (see box).

Microplastics and Microbeads

It is worth mentioning the particularly ubiquitous nature of microbeads and microplastics in this list. Microplastic is generally defined as plastic particles ranging from 100 nm to 5 mm in longest dimension while nanoplastic is plastic particles less than 100 nm⁹. Marine microplastics can originate from two sources; either they were originally manufactured as small particles (primary) or resulted from the breakdown from larger items (secondary).

Primary microbeads include industrial ‘scrubbers’ used to blast clean surfaces, plastic powders used in molding, micro-beads in cosmetic and personal care products, plastic nanoparticles used in a variety of industrial processes, and spherical or cylindrical virgin resin pellets used in plastics manufacturing.

Key sea-based sources of marine plastics

- Merchant shipping – rope, galley waste, cleaning
- Military activities – waste disposal
- Fishing – nets, boxes, rope, wrapping bands, galley waste
- Aquaculture – nets, floats, rope
- Offshore oil and gas platforms – galley waste, sewage
- Cruise ships – galley waste, sewage-related (may be equivalent to a medium-sized town)
- Recreational boating – galley waste, sewage-related

Key land-based sources include coastal tourism

- Plastic packaging
- Cigarette filters
- Population centers – sewage, storm drains, street litter
- Horticulture/agriculture – plastic sheeting, tubing
- Poorly controlled waste sites and illegal dumping
- Industrial sites – plastic production and conversion, packaging
- Microplastics from waste water containing synthetic clothing fibres.

⁹ Microplastics.Science (<http://microplastics.science/what-are-microplastics/>)

Secondary microbeads result from the fragmentation and weathering of larger plastic items. This can happen during the use phase of products such as textiles, paint and tires, or once the items have been released into the environment. The dominant cause of degradation of plastics outdoors is solar UV radiation, which facilitates oxidative degradation of polymers.

Microplastics can be toxic on two levels: they can be inherently toxic, leaching toxic chemicals (discussed above) and, due to their hydrophobic nature, they can absorb and concentrate toxic pollutants present in the environment (e.g., pesticides, PCBs). Smaller particles (<100µm) have more surface area per unit volume and therefore exhibit more intrinsic toxicity, elevating their potential to cause damage at the biochemical level (GESAMP 2015, Kershaw 2015).

A number of studies have shown that a variety of marine organisms ingest microplastics, including fish-eating birds, marine mammals, fish, invertebrates, and zooplankton. Microplastic particles can be passed through the food web as predators consume prey who have ingested microplastics. The potential accumulation of microplastics in the food chain, especially in fish and shellfish could have consequences for the health of human consumers. This is particularly the case for filter-feeding bivalves such as mussels and oysters (Sussarellu *et al.* 2016). A recent study measured the occurrence of microplastic in seafood available to consumers and found the presence of microplastics in more than 25% of individual animals and over half of all species purchased and/or collected from fish markets and fishermen selling fish for human consumption (Rochman 2015). This study supports the concern that chemicals from marine microplastics may be transferred to humans through diets containing fish and shellfish, and adversely impact human health.

Human Health Impacts

After almost a century of production, use, reuse, recycling and end of life (including destruction and landfilling) of plastic products, interaction and association of chemicals in plastic debris in the environment and their impacts on human health have yet to be studied holistically across terrestrial, freshwater and marine ecosystems. Studies and observations to date show that plastics can have a negative impact on all living organisms, and increasing numbers of studies and literature reviews on the exposure and toxicity of additives in plastics for humans, on the persistence of plastics in environmental media, and on the impacts of microplastics in personal care products and in the oceans, are being published in scientific literature and reported in public media (Keswani *et al.* 2016, Ziccardi LM *et al.* 2016, Bouwmeester *et al.* 2015, GESAMP 2015, Kershaw 2015). As researchers attempt to understand the impact on biota, significant attention to this subject has been prompting studies on the endocrine disruptive properties of plastic additives and the follow-on impacts on fertility, cancer, metabolic disorders, and gender-related behaviors (National Institute of Environmental Health Sciences 2016).

Endocrine Disrupting Chemicals

The National Institute for Environmental and Health sciences writes that a growing body of evidence suggests that numerous chemicals, both natural and man-made, may interfere with the endocrine system and produce adverse effects in laboratory animals, wildlife, and humans (WHO, 2012). Scientists often refer to these chemicals as “endocrine disruptors.” Endocrine disruptors may turn on, shut off, or modify hormonal signaling, which in turn may affect the normal functions of tissues and organs,

especially during early development. Many of these substances have been linked with developmental, reproductive, neural, immune, and other health impacts in wildlife and laboratory animals. A growing body of evidence suggests that these substances are also adversely affecting human health in similar ways, resulting in reduced fertility, early puberty in females, and increased incidences or progression of some diseases, including obesity, diabetes, autism, endometriosis, and a number of cancers (e.g., breast, ovarian, testicular, and prostate). Chemicals that mimic or interfere with the actions of naturally occurring estrogens are defined as having estrogenic activity, which is the most common form of endocrine disruptor activity (Manikkam 2013, Birnbaum and Fenton 2003, Yang *et al.* 2011). Endocrine disruption triggered by chemicals related to plastics are of particular interest in the scientific community (National Institute of Environmental Health Sciences 2016).

As described earlier, thermoplastics are made by polymerizing a specific monomer or monomers in the presence of catalysts into high-molecular-weight chains known as thermoplastic polymers. The resulting polymer is mixed with small quantities of various additives (antioxidants, plasticizers, lubricants, etc.) and melted, mixed, extruded, and pelletized to form a base thermoplastic resin. Base resins are either used as-is (e.g., bisphenol A (BPA)-based polycarbonate) or mixed with other resins, additives, colorants, and/or extenders to form the final plastic compound. Plastic products are then made by using one or more polymer compounds or resins that can be subjected to finishing processes that may use inks, softeners, adhesives, and so forth, to create a commercial product. Thus, plastic products contain a variety of monomers, oligomers, catalysts and additives that may exhibit endocrine disrupting activity (EDA) because they have physicochemical properties that enable them to bind to steroid hormone receptors (e.g., estrogen, androgen and thyroid receptors).

Because polymerization of monomers is rarely complete, and additives are not chemically bonded to the polymeric structure, chemicals having EDA can leach from plastic products that individually or in combination can produce adverse health effects, especially in prenatal to neonatal mammals. This leaching of monomers (e.g. BPA from polycarbonate) and additives from a plastic item is often accelerated if the product is exposed to common stresses of use and/or environmental exposure, such as ultraviolet (UV) radiation from sunlight, microwave radiation, and/or moist heat from boiling or dishwashing (Yang *et al.* 2011).

The exact chemical composition of most commercially available plastic products is proprietary and not known. A single part may consist of 5–30 chemicals, and a plastic item may consist of ≥ 100 chemicals, almost all of which can leach from the product, especially when stressed. A recent survey of over 500 plastic consumer products were shown to release chemicals having detectable EDA, especially if they were exposed to common-use stresses (Yang *et al.* 2011).

In response to market and regulatory pressures, BPA-free plastic products have recently been introduced as replacements for polycarbonate resins. However, replacement resins and products tested to date release chemicals having EDA, sometimes having more EDA than BPA-containing polycarbonate resins or products, especially when exposed to UV light (Bittner *et al.* 2014).

Health Impacts Associated with Disposal: Incineration and Waste to Energy

Since plastic recycling is gradually becoming economically nonviable due to the low cost of petroleum, incineration of plastic waste is becoming a preferred waste management alternative. Waste incineration systems produce a wide variety of pollutants which are detrimental to human health. The most dangerous emissions can be caused by burning plastics containing organochlorine-based substances like PVC. When these plastics are burned, harmful quantities of dioxins, a group of highly toxic chemicals, are emitted. Dioxins are endocrine disruptors, neurotoxins and carcinogenic to humans. Once ingested, they persist and accumulate in body fat, and can be passed mother to child via the placenta or through breast feeding. Even modern incinerators release toxic metals, dioxins, and acid gases. Waste incinerator systems also produce toxic ash and other residues (Thornton et al. 1996) for which safe disposal options must be sought.

The waste-to-energy energy recovery is technologically incompatible with reducing dioxin emissions. When energy recovery is employed, it requires heat exchangers which operate at high temperatures, maximizing dioxin production. If the gases are quenched, it goes against energy recovery (STAP 2011).

The affected population includes those living near incinerator sites, as well as those living in the broader region. Some documented routes of exposure to toxic chemicals via incineration include (Thornton et al. 1996):

- Inhalation of contaminated air (can include both workers at the site of incineration, and persons living in proximity);
- Consumption of locally produced foods or drinking water that have been contaminated by air pollutants from the incinerator; and
- Consumption of fish or wildlife that have been contaminated by the air emissions.

The pollutants created in any incineration process, even if trapped, will still reside in filters and ash, which require special landfills for disposal. If no such disposal sites are available, or are mismanaged, the dispersal of toxic ash into the environment presents real exposure for flora and fauna.

Water-borne Diseases

Discarded plastic, such as plastic bags or plastic sachets¹⁰, can clog storm drains and result in flooding. Discarded plastic containers and on-land accumulations, especially in marshy areas such as mangrove forests, can retain water in and of themselves, creating opportunities for stagnant water pools to form. Stagnant water is an ideal habitat for mosquitoes and other parasites which have the potential to spread a large number of diseases, such as malaria, dengue fever, Zika virus, chikungunya and encephalitis.

Public Health Impacts of Marine Plastics

Understanding the potential health risks to humans via the seafood pathway is predicated on understanding the various pathways by which plastic and chemical pollutants enter the marine environment and subsequently the marine food web, such as the research done by Chelsea Rochman,

¹⁰ Used in Africa and Central America for drinking water

Ph.D. Her laboratory experiments with adult *medaka* indicate that ingestion of microdebris results in the transfer of toxins to the food web (Rochman *et al.* 2013). Dr. Rochman cites studies that demonstrate this transfer occurring in the marine environment. Dr. Rochman notes that higher brominated polybrominated diphenyl ethers (PBDEs) in particular appear to enter the food chain from microplastics, and that the question is not whether these constituents make their way to humans, but in what quantity. In her 2015 paper, Dr. Rochman demonstrates how plastic is being consumed by humans via market fish in Indonesia and in California (Rochman *et al.* 2015).

Economic Impacts of Plastic Pollution

Plastic waste accumulations along beaches and coastlines cause economic damages to tourism and stress the waste management systems' capacity to manage waste flows.

In its 2014 report, "Valuing Plastic: The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry" Achim Steiner, the former UNEP Executive Director, writes that "The total natural capital cost of plastic used in the consumer goods industry is estimated to be more than US\$75 Billion per year. The cost comes from a range of environmental impacts including those on oceans and the loss of valuable resources when plastic waste is sent to landfill rather than being recycled." The total natural capital cost of marine eco-systems alone is estimated at US\$13 Billion per year.

There is no question that the economic costs of improper lifecycle management of plastic waste, especially including the economic costs of threats to human health, are substantial and present. An urgent need and motivation is required to address this problem.

Depletion of Fossil Fuel and Natural Resources

Sources vary, but most recent data shows that approximately 4-6% of the world's oil production is used to make plastics (McKinsey *et al.* 2016), with about half of that used in manufacturing. This is in addition to the natural gas used as material feedstock. The Ellen MacArthur Foundation's recent report (McKinsey *et al.* 2016) points out that if the current growth of plastic production continues, the consumption of oil by the plastics sector will account for 20% of global oil consumption by 2050. The same report points out that this is equivalent to the oil consumption of the entire global aviation sector, and is in addition to the use of natural gas as material livestock and fuel. In fact, the increase in demand for oil by the plastics industry (growing by 3.5-3.8% annually) far exceeds the overall demand for oil, expected to grow by only 0.5% annually (McKinsey *et al.* 2016).

It should be noted that In the United States, plastics are manufactured from hydrocarbon gas liquids (HGL) and natural gas. HGL are byproducts of petroleum refining and natural gas processing. These liquids are used as feedstocks by petrochemical manufacturers to make plastic and are used as fuels in the manufacturing process. Production of natural gas involves recent innovations in hydraulic fracturing which affects land use and water consumption, methane emissions, air emissions, water contamination, noise pollution, and health. Water and air pollution are the biggest risks to human health from hydraulic fracturing (Meng and Ashby 2014).

Emergence of Global “Hot Spots” of Plastic Pollution

As a result of the rapid growth and expansion of plastic pollution, global “hot spots of plastic pollution” have emerged on land, in the waters (freshwater and marine environments) and in human bodies.

The first widely documented plastic pollution “hot spot” was the so called “Great Pacific Garbage Patch”, reported by Captain Charles Moore as early as 2004. His journey was documented in National Geographic’s *Strange Days on Planet Earth* (2008), and was followed by a wave of public awareness, culminating with the emergence of hundreds of outreach and advocacy groups around the world working on plastic pollution. Continued investigation produced a deeper understanding of the nature of ocean currents, and the emerging understanding of the existence of multiple oceanic gyres has become the focus of studies by Algalita Foundation (founded by Captain Charles Moore) and 5 Gyres Institute.

Plastic pollution impacts on the ocean are only partially understood, and increasingly, environmental organizations are pointing to land-based sources of pollution as a key concern, as well as their focus on cruise-line and fishing industries’ contribution to the problem.

About half the global population lives within 100 km of a coastline, and population growth is greatest in that zone (UNEP 2013). The projected growth of coastal population by year 2050 (United States Census 2015) combined with the accelerated rate of consumption by middle class make it likely that plastic pollution in the ocean will continue to grow unless substantial changes are made on land.

Particularly concerning are the trends associated with plastic pollution generation and leakage within developing countries, as observed by the recent McKinsey report (McKinsey *et al.* 2015). These trends have given rise to a quick response directed at building massive recycling facilities and waste catchment systems. While this is necessary, it is only *a first step to harnessing the problem*.

Very important consideration must be given to the nature of conventional petroleum-based plastic as the packaging material of choice. The regional GEO 6 report¹¹ launched at the UNEA-2 conference assigns special consideration of this issue for the developing countries.

Complexity of the Global Plastic Pollution Problem

What makes the plastic pollution problem so difficult to solve?

Rising public awareness of discarded plastic packaging increasingly generates negative brand association and brings risk to business, as is well described in the UNEP 2014 Report, “Valuing Plastics” (UNEP 2014). The response from the business community has been to front prominent recycling campaigns and to lend support for outreach and education about the benefit of recycling such as “Don’t Waste. Create”, “Happiness Recycled”, “I Want to be Recycled” and others. Harvard Business Review reports that companies like American Airlines, Bell Atlantic, United Airlines and Coca-Cola have made buying recycled products and investing in green R&D part of their overall business strategies (Biddle 1993).

¹¹ <http://web.unep.org/geo/>

In the search to finding cost effective alternatives and solutions, it is important to understand the strategic and often conflicting interests of the various stakeholders, whether industry, public, consumer advocacy organizations, investors, or entrepreneurs. It is equally important to identify the expected technical and economic performance aspects of any alternative materials.

The growing plastic production is one of the major contributors to the problem of plastic pollution, and paradoxically, the plastic industry is the target customer for products and materials that might replace conventional plastics. Their motives or incentives for accepting or resisting change must be well understood and considered.

Managing Costs

Global production of plastic leans on natural gas (in the United States) and petroleum in the rest of the world. Today, in the wake of innovation in shale oil and natural gas extraction, it is easy to speculate that there will be no better (economic) alternative for plastics feedstock than plastics.

For solutions, we can look to the lessons from other fossil fuels, such as coal. Because the externalities of using coal (land degradation, health impacts, emission impacts on air and water) were properly quantified, even today, the availability of cheap coal is not enough to make society lean on it exclusively. If the same was done for plastics, low oil prices would not singularly drive plastics production from virgin fossil fuels and virtually eliminate incentives for its responsible management and the drive for innovation. Governments and private citizens must put a full value on the costs of plastics management and impacts.

Waste Capture and Recycling in a Fossil Fuel-based Economy

The dropping commodities prices will almost entirely erase any possibility to build value in a residual product made from collected and recycled plastic.

During the past 10 years, there was a short-term hope that plastic could be collected, recycled and turned into a valuable end product, such as textile or fences, patio products, and other goods. This waste-to-value conversion would result in a final product whose market value would be enough to pay for the collection and handling of plastic waste, whilst creating a modest livelihood for entire communities. Waste-to-value innovation is a growing interest for many developing countries who view plastic pollution as an important economic sector and source for alternative energy.

While the price of oil was over US\$80 / barrel on the global commodities market, this appeared a viable alternative. Businesses were created to collect rPET (a valuable recycled material) and to produce various valuable end products. One such business is [Thread International](#), operating in Haiti and Honduras. Thread processes the rPET into fabric threads that it sells into existing supply-chains and contributes to the production of “responsible” fabric used by apparel manufacturers such as Patagonia, Columbia and others. By creating incentives to collect rPET bottles, Thread has been able to generate revenues for entire communities. Others, like Coca Cola, rely on rPET material for in bottles in 24 countries around the world. In 2014–2015, Coca Cola helped open new rPET production plants or production lines in China, Japan, Taiwan, South Africa, Ecuador, Colombia, Costa Rica, Guatemala, and Mexico (Coca-Cola 2015).

However, these opportunities are exposed to the market volatility of crude oil, which dropped to six-year lows in 2014 (Macrotrends 2016). This in turn reduced the cost of virgin PET and increased the cost of the recycled rPET, wiping out the economic incentives to collect plastic waste. As a result, the mountains of uncollected PET bottles are growing, and communities whose livelihoods were connected to recycled plastic can no longer earn a living. This has been reported by the Think Beyond Plastic team during recent site visits to Central America, South America and Africa.

Recycling, while generally necessary and effective for other materials, has been subject to volatile market conditions and overcapacity, and has not proven a successful match to the exponential growth of consumption of disposable plastic.

Since 2014, major recyclers have seen their advantage erased by the dropping oil prices. In the U.S., many cities and towns pick up household plastic and sell to recyclers who sort, process and resell the scrap. These municipalities typically earn cash for selling recyclable materials under contracts that tie the sales price to commodities prices, with a minimum price guarantee. In recent months, however, many expiring contracts have been replaced with new contracts that set no such floor (such as the Association of New Jersey Recyclers). That raises the possibility for some municipalities that a moneymaker could turn into a loser (Kantchev and Ng 2015).¹² There have been notable business failures of major recycling plants in Europe.¹³

Protecting Jobs

The plastics industry offers jobs to millions of people worldwide. Plastics Europe reports that over 1.45 million people were employed by the plastics industry in Europe in 2015. In the US, that number is almost 900,000 people. In India, the plastics market employs 3 million people in over 25,000 companies. These people collectively generate revenue well above US\$500 Billion each year in the plastic industry¹⁴ alone.

Protecting the jobs and livelihoods of these people must be a key consideration for any innovation or new material. These trained professionals also represent a valuable human capital and talent that could be applied to the manufacturing processes for new materials. Thus, *any new solutions must necessarily include job creation and investments in alternatives that would replace existing revenues, create new revenue streams, and result in new jobs and new opportunities.*

Increased Competition

Commodities' prices aren't the only culprit in the shrinking recycled plastics market. Well-intentioned government policies have pushed companies to use more recycled materials, and recycling plants have mushroomed in the U.S. and Europe. This move has created an oversaturation in the recycling sector that has become evident now that demand for recycled plastic has shrunk. In the developing world, the

¹² Statement from Dominick D'Altilio, president of the Association of New Jersey Recyclers: "They are definitely concerned about the possibility that they may have to pay for the materials to be removed".

¹³ In Europe, two German recyclers have gone bankrupt in 2015. ECO Plastics Ltd., a British firm that touted in 2012 the opening of what it called "the world's largest plastics processing facility," went into administration, a form of bankruptcy.

household items, coatings for furniture and doors, construction materials, automotive industry parts, agricultural plastic, medical services, and disposable plastics, just to name a few.

The variety of plastic products is of great consumer value, but represents a challenge to the recycling industry. Different types of plastics often require different processing and may be subject to a different contract by Waste Management. Not all of them can be recycled easily, not all of them can be captured easily and they often have different value to recyclers. As complexity of products grows, so does the difficulty in managing these contracts and the actual end of life processing.

Managing Risks Associated with Shifts in Production Processes

Large corporations are usually slow to effect change since they must protect revenues, costs, and thus, the status-quo, systems, and infrastructure in which they have invested. Major multinational corporations typically staff and maintain large R&D departments and have demonstrated evolution in material and series of innovations that have benefitted their bottom line. However, disruptive innovations almost always start with small and lean businesses. Biotech did not start within the walls of large pharma – it took scientists and entrepreneurs from university labs to lead the wave of innovation¹⁶. Qualcomm, once the world's leading provider of wireless services (SBIR 2011), was started by an MIT and a Cornell graduate, with an NSF SBIR grant. This was also true in the entire history of high-tech, for both software and hardware innovations¹⁷. Based on this history, it is reasonable to expect that the surge of innovative materials and alternatives to conventional plastics would come from small startups.

Takeaway: a new venture that has a patented technology and / or innovation will de-risk the innovation for a large businesses, and presents an opportunity to reduce time-to-revenue while meeting urgent and pressing innovation needs for any large company.

Inherent Design Flaws of Plastic Packaging

Manufacturers who have chosen plastic as a packaging material of choice have realized a substantial savings in cost; but in making this decision, they inadvertently created the paradoxical situation where the benefits and drawbacks of their products often compete:

- Plastic has helped slow the depletion of valuable natural materials such as cork, silk, wood, and others, yet is causing the depletion of fossil fuels;
- Plastic products are *lightweight* which results in substantial CO2 savings, but also makes them prone to unintentional distribution across the environment as litter;
- Plasticizer compounds and additives help create plastic packaging that keep food safe from biological contamination, beautifully presented, and long-lasting; yet the same additives are

¹⁶ Witness the rise and growth of Genentech, a leading bio-technology company, a subsidiary of Roche.

¹⁷ Examples too numerous to mention, but a simple look at Apple computer (personal computers), Sun Microsystems (servers), Google and Netscape and hundreds more support this view.

well-known and documented carcinogens and endocrine disruptors with long-lasting impacts on public health (NIH 2015);

- Plastic packaging has a *life expectancy of hundreds of years* (Bio-Tec Environmental 2016), which has allowed for long shelf-life and substantial cost savings to producers; yet it is also used for single-use and disposable products, which makes plastic waste accumulations practically indestructible in the environment;

The very qualities that provide marketing and economic advantages to manufacturers are often the qualities most closely linked to the environmental and human health damages of plastic packaging.

Takeaway: Any new material that is introduced as an alternative to the current conventional plastics must carry forward the desirable price and performance properties of plastic without the toxicological and pollutive downsides.

Life Style Choices and Consumer Demand

In the US, the early introduction of plastic to society was closely linked to growing post-war consumerism. There were other cultural and economic forces at work -- the rise of suburbia; the development of fast food restaurants; and the building of the interstate highway system, which was a major factor in the death of refillable bottles because bottlers no longer were limited to regional distribution networks. It was at a time when women were joining the workforce in droves, yet their

traditional roles of caretaker and homemaker had not changed. The young plastic industry, looking for a customer, was able to deliver a great promise: convenience, achieved through the easy luxury of disposability. The necessary analog to disposables was plastic as the material of choice.

The most famous visual icon of this time period was the 1955 Life Magazine article, "Throwaway Living."

Today, the emerging economies of China, India, and Brazil are quickly developing a middle class, with more disposable income and higher consumer demand. *Plastics News* reported a study shared at the Southeast Asia Plastics and

Rubber (Vietnam 2014) show that stated that Vietnam's middle class will triple by 2020. Rising income levels and growth in the middle class are likely to increase the

consumption of packaged consumer goods such as beverages and processed foods, thereby enhancing the demand for plastic packaging (Lucintel 2013). If any of these countries are able to achieve such sustained expansion in the ranks of their middle-class households, then their appetites for plastics packaging could expand quickly.

Takeaway: It is worth considering the performance expectations of the consumer for any alternative (outside of the previously discussed desire for avoidance of toxicological threat).



Figure 5. "Throwaway Living", Life magazine, Aug. 1955

Convenience

Convenience appears to be one of the key advantages of disposable plastics and is one of the most important features of today's disposable plastic packaging and plastic items.¹⁸ Consumer demand for convenience is an essential requirement that businesses raise to meet. By comparison, reusability is often considered as inconvenient, and not always well aligned with today's very mobile lifestyles.

Takeaway: It is worth considering products and materials that can support the need for convenience and the trends toward disposability, which are still heavily relied upon by businesses.

Disposability

The marketing campaigns that glorified the “throwaway” lifestyle connected disposability with convenience. Today, disposability continues to be an essential customer need and a key marketing feature, as evidenced by the fast rise of the packaging sector of the plastics industry. Disposable packaging is a great example of a linear business model, as the Ellen MacArthur Foundation report (McKinsey *et al.* 2016) correctly points out. Disposable packaging is also connected to the growth of middle class and their consumption habits.

Takeaway: Disposability is an important consumer requirement for any alternative to plastic.

Affordability

Externalizing costs has allowed manufacturers to keep the price of plastic consumer products and packaging exceptionally low. Choosing an alternative such as wood, glass and metal is often price-prohibitive.

Takeaway: Alternative materials and products must be able to maintain the pricing value for consumers. This may be achieved through a variety of methods, including subsidies for alternative materials or cheap feedstock.

Health Safety

Growing awareness of the impacts of endocrine disruptive chemicals on the human body (Ruthann A. Rudel, 2014) has become a key trend in developing products for babies and toys for children. A plethora of products on the market claim the “BPA-free” and “EA-free” labels.

Takeaway: Alternatives to conventional food packaging and those that come into contact with humans (such as toys) must include safe and non-toxic chemicals.

In conclusion, these trends have become deeply embedded in what consumers expect from their plastic packaging and plastic products. Behavior change towards reusability will be very difficult and unlikely to match the exponential growth of the production of conventional plastic. On the other hand, if the consumers continue to demand disposable packaging, the answer can be a material that biodegrades without toxic residue in the environment.

¹⁸ Marketing campaigns by Unilever, Procter and Gamble, TBD here

Exploring Modalities to Harness Plastic Pollution

The reports and studies cited thus far in this report indicate that disposable plastics – items made for the specific purpose of discarding after use – appear to be the most problematic category of plastics as relates to environmental and human health. Collectively, these items are often referred to as “packaging”.



Figure 6. The New Plastics Economy (McKinsey *et al.* 2016)

The figure above illustrates this phenomenon: less than 14% of global plastic production is recovered and processed in some way, with the remaining 86% of destined for landfills, or to be released in the environment. As plastic has a life span of hundreds of years, and such distribution to environmental media may be swift, plastic trash accumulations remains long-lived in the environment, with lasting physical and toxicological impacts to organisms. Capture of plastic waste in landfills does not necessarily prevent its eventual release to the oceans, and the projected growth of production and consumption of conventional plastics will likely render the current model of life-cycle management even more redundant (McKinsey *et al.* 2016).

This section of the report will examine some of the underlying issues, the pros and cons of recommended solutions, and suggest a more holistic approach to the issue. It will identify strategic investments for the GEF’s best use of limited resources to spark incremental activities, spur innovation, and generate global environmental benefits through the reduced exposure of biota to the physical and toxicological impacts of plastic pollution.

Towards a Circular Economy Approach

It is widely acknowledged that the circular economy concept began to take shape through the 1981 report of Walter R. Stahel and Genevieve Reday-Mulvey, produced for the then Commission of the European Communities, “Potential for Substitution of Manpower for Energy.” The report focused on reconfiguring the previous “open-ended” mentality of economics, with a focus on extending the service-life of buildings, and highlighting the inherent waste of disposing of old products instead of repairing them (Stahel and Reday-Mulvey 1981).

In 2016, Nature Magazine revisited the circular economy model and described that it “... looks to extend the life of products at the 'use' stage, retaining value and designing out harmful by-products such as toxic substances, to create the perfect habitat for ecologically innovative companies (Kiser 2016) “.

Today, this thinking has received significant refinement and is defined loosely as an economy that is “restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles” (McKinsey *et al* 2016).

One of its leading champions is the Ellen McArthur Foundation, which has pioneered circular economy approaches to various sectors of industry, and has adopted as its mission to accelerate the global transition to circular economy.

The circular economy approach can be effective in reducing plastic pollution if a two pronged investment approach is employed:

- **Upstream** – decoupling from fossil-fuel feedstocks and investing in the development of bio-benign, cost-effective, high performing, biodegradable, non-toxic materials and *plastisizers*, made from non-food grade agricultural biomass, agricultural waste and other sustainable feedstocks, such as the naturally occurring biopolymers, as described further in this advisory.
- **Downstream** - capturing and recovering all existing and new plastic waste with appropriate waste stream separation to enable reuse, and possibly remove toxicity of leached *plastisizers*, which would replace virgin fossil fuels.

With focus on material innovation and investments *upstream*, industry could maintain its projected increase in consumption and protect jobs, while pivoting towards sustainable materials; meanwhile, smart investments *downstream* will produce innovations that reduce leakage and will accommodate a variety of new materials. Such an approach will ensure that the materials in the system support the realization of the circular economy in a virtuous cycle of non-toxic materials.

In its 2011 Report on Marine Debris, the STAP first proposed that industry, government, and consumers come together to consider an expansion of thinking to the Five Rs-- Reduce, Reuse, Recycle, Redesign, and Recover-- and suggesting that these be considered in a regional seas management context (STAP 2011). This report presented land-based sources of plastic pollution as a key contributor to marine debris; it considered the inadequacy of end-of-pipe solutions, and the need to address unsustainable production and consumption of plastic products. This included the design and marketing of plastic products without appropriate regard for their environmental impact or actual (vs theoretical) ability to

be recycled in locations where sold, particularly when inadequate waste management infrastructure and inappropriate disposal is common globally.

This current report is looking to identify actions that can have global impact, irrespective of region, with heavy focus on reduction of harmful chemical and waste through material and manufacturing redesign and material, and associated innovative ways to enhance recycling and recovery.

The Sixth Replenishment of the GEF (GEF-6) saw the Chemicals and Waste Focal area, Strategic Objective 2, seek to “reduce the prevalence of harmful chemicals and waste and support the implementation of clean alternative technologies/substances”(GEF 2014). Programme 6 of this Strategic Objective specifically seeks to “support regional approaches to eliminate and reduce harmful chemical and waste in Least Developed Countries (LDCs) and Small Island Developing States (SIDS)”.

In its Innovative Programming Options there is a strong focus on finding ways to encourage Private Sector Partnerships through projects that encourage, *inter alia*:-

- (a) Innovative environmentally sound waste reduction projects;
- (b) Technology demonstrations;
- (c) Recycling and waste-management through micro, small and medium enterprises;
- (d) Economic instruments and business models to facilitate income generation for chemicals and waste management including waste recycling and extraction of valuable constituents of waste, and
- (e) Life cycle and green chemistry investments

It is within this strategic lens that potential solutions and approaches are presented, exploring most current research in innovations and regional pilots, and how it can support the GEF strategic objectives, even into GEF-7 and beyond.

Beyond End of Life Strategies

Efforts to tackle plastic pollution have been many, and most of them have a strong focus on end-of-life management, such as increasing collection, recycling, cleanups, demonstrating the value of waste plastic, and deriving economic benefits from processing the final plastic waste product¹⁹.

As early as the 1950-ies, businesses that use disposable packaging have invested in broad-based campaigns encouraging recycling while continuing to promote the use of disposables, and marketing the benefits of cost, convenience, and in some instances, even the sanitary, health, and environmental benefits of disposable single-use plastics (Ecocycle 2006).

Keep America Beautiful was founded in 1950 by the American Can Company and Owens-Illinois, two giants in the packaging business who clearly understood how recycling would help their growing business. Its most popular campaign, “The Crying Indian” carefully places a special focus on personal responsibility. By 1980, there were more than 5,000 recycling municipal facilities in the United States. The focus on recycling paid off, and in 1993 the US EPA reported a raise in recycling from 7% to almost 23%. Today, more Americans are likely to recycle than to vote (Platt and Seldman 2000). The Keep

¹⁹See previous references. Also see work of the Ocean Conservancy Trash Free Seas Alliance.

America Beautiful Campaign receives millions of dollars per year from “some 200 companies that manufacture and distribute the aluminum cans, paper products, glass bottles and plastics that account for about a third of the material in US landfills” including Coca-Cola, McDonald’s, 3M and Scott Paper. It is also funded by waste companies that landfill and incinerate hazardous wastes and prefer the focus of waste disposal to be on the tidy disposal of litter. The Campaign’s directors include representatives of Philip Morris, Mobil Chemical and Procter and Gamble and PR giant Burson-Marsteller.

The focus on end-of-life management is understandable: it protects revenues and business growth, it allows for an uninterrupted growth in production and consumption of conventional plastic; and maintains the current investments in infrastructure. This approach creates the sense that most disposable plastic waste can be captured, given the necessary level of investment in infrastructure (often using public funds) such as recycling or incineration. This approach fails to acknowledge that plastic material is always present, and just changes state from one type of polymer, to another and in a sense, what is referred to as recycling is actually *downcycling*. With global recovery rates for plastic averaging 14% (McKinsey *et al.* 2016), end of life management can only marginally improve the trash accumulation, but *does not address the problem at its core*.

Another aspect of this problem is that plastic trash is not inert, and the toxic compounds used as *plasticizers* in the manufacture of plastic products persist. Incineration (as previously discussed) is a particularly harmful method of disposing of plastic waste, since releases of toxic fumes to air as well as the solid residuals or ash are highly toxic, profoundly affecting air and water quality. A common disposal mechanism in developing countries is open fire incineration, which can considerably facilitate the release of semivolatile persistent substances like BFRs from plastics and other polymers. And even landfilling is not a panacea, since landfills frequently catch fire even in industrial countries. According to a U.S. Fire Administration report in 2001 (US Fire Administration, 2001), an average of 8,300 landfill fires occurs each year in the United States. Landfill fires are a major source of unintentionally POPs including chlorinated. E.g. in an assessment of POPs releases from landfill fires high levels of PBDE were detected and PBDD/F levels were similarly high as PCDD/F (Gullett BK, 2010).

Ocean and Beach Cleanups

Multiple attempts at ocean cleanups have been proven inadequate to the task. There have been recent feasibility studies to explore an Ocean Clean-Up array to tackle the plastic pollution from the North Pacific Gyre, and this projected a clean-up efficiency of just 42% in 10 years, using a 100km array. Estimated costs for such an array would run at €37.1 million a year, which translates to just €4.53/kg of collected ocean debris (Boyan Slat 2014). In addition to the economics, the recent deployment of the pilot installation resulted in a technical malfunction caused by ocean currents and strong winds, one of the greatest feasibility issues warned against by the science community reviewing the approach.

Beach and community cleanups, on the other hand, are a great educational tool to demonstrate the key sources of plastic pollution. [Let’s Do it World!](#) is a global organization of over 14 million volunteers, producing a one-day clean-up event in over 130 countries. The increase of plastic trash is a repeated theme during their annual conference, and a consideration for many of their volunteer organizations. Ocean Conservancy, a US-based NGO, coordinates an annual international beach cleanup. It reports the top 10 trash items, 8 of which are plastic (Ocean Conservancy 2014). They readily admit that cleanups

alone will not solve the pollution problem (Ocean Conservancy 2014). As a result, Ocean Conservancy convened the Trash Free Seas Alliance with the purpose of bringing businesses together around a solution that prevents plastic waste leakage into the ocean.

The take home message, however, is that moving plastic waste from one location to another, or transforming it from one type of pollution to another (e.g., through incineration, waste to value) does not eliminate the problem of plastic pollution, since ultimately it still results in growing accumulations of plastic material and toxic residue.

Reducing Consumption and a Culture of Reusability

Frustrated with the issues surrounding plastic pollution, consumer advocacy organizations are urging the public to reduce consumption of disposable plastic.²⁰ This might be a desirable outcome, but our reliance on disposable plastics has complex socio-cultural, economic and technological aspects, such as:

- **Cultural value systems and lifestyles.** Various bilateral and multilateral exchanges between the STAP and client countries of the GEF have indicated a mixed attitude to plastic, i.e. despite the growing awareness of the problems with plastic trash, plastic is also seen as a sign of modernity, and a desirable attribute of the growing middle class that aspires to US and European lifestyles.
- **The convenience of disposable plastic,** heavily marketed since the 1950ies has gained a very strong foothold in the global consumer attitude. Convenience is considered a key attribute and consumer requirement, and disposability has been strongly linked to it through powerful marketing campaigns.
- **The low price of plastic packaging.** In the current economic model, which does not consider the fully burdened cost of packaging, plastic is the cheapest and most effective food packaging alternative. In addition, plastic packaging offers long shelf-life, lower transportation costs, and a clear advantage for food presentation. Other packaging materials (glass, paper, metal), though all recyclable, have been marginalized in favor of plastic for various economic and environmental reasons. In some instances, they are re-emerging as a food and beverage materials of choice in the upscale and organic food market, but that is still a very small sector. Thus, economically disadvantaged communities are disproportionally exposed to the toxic impacts of plastic packaging.

Policy and Bans

Research for this advisory document has not discovered any policies on record that encourage innovation for alternatives or that offer incentives to manufacturers to incorporate sustainable alternatives to conventional plastic, or for consumers to utilize sustainable alternatives.

There is little to nothing in the literature that addresses ways to generate the appropriate science-to-policy, fiscal, and economic environment to incentivize innovation creation and implementation of

²⁰ Breast Cancer Fund, Plastic Pollution Coalition, Environmental Working Group, Algalita, 5 Gyres to name just a few.

alternatives. Rather, in many developing countries, focuses on bans, and fiscal tools of limited focus (usually related to punitive taxing for inadequate waste management, or in better cases, related to providing tax breaks for importers willing to bring in alternatives) have been most commonly promoted, with variable success²¹. But bans will only succeed where there are cost-effective alternatives readily available. Also, they must be enforceable.

In all instances where bans have been successful, they have created a market demand for alternatives and prompted the emergence of countless reusable bag businesses in Europe and the United States²², the emergence of an entire cottage industry of artisanal reusable bags in Africa, Central America and South America²³, the emergence of reusable plastic, glass and metal bottles and the re-emergence of pulp-based businesses for paper products such as clamshells, paper bags and packaging etc²⁴.

Most challenging of all is finding that balance of focus and comprehensiveness that makes a broad policy on plastics or *plastisizers*, meaningful. Highly specific policies become redundant as the target is achieved; or worse yet, can open the door to more harmful alternatives if not appropriately thought through. A good example of this is the ban on Bisphenol A (BpA). This ban has created a marketing advantage for the next generation of Bisphenols – a *plastisizer* compound-- now unregulated, from the same chemical family, with similar properties, used in the manufacture of many plastic products. The BPA ban has allowed massive “BPA-free” marketing, with no consumer health benefits over the traditional BPA. Studies (Certichem, "EA- Free Plastics") have proven that BPA-free products are leaching a substantial amount of estrogenic compounds.

It is equally challenging to find policies that can address the more systemic aspects of plastic pollution in all its forms and from the broad sources of its origin. The heterogeneity of sources and sectors to be addressed has made it clear that development and implementation of policies that address the plastic pollution problem will require political, public and private sector will. It will also require close coordination between government, industry, the scientific community, NGOs, and the public, supported with the appropriate revenue generating infrastructure to effect the relevant technology conversions, changes in consumptive behaviors, and waste management practices. See Appendix II for a case study.

Early Material Innovation: Bioplastics

Bio-based and biodegradable polymeric materials represent some of the early efforts to identify a suitable alternative to petroleum-based plastic, to protect the depleting petroleum resources, and to reduce CO₂ emissions into the atmosphere. Leading biodegradable plastics enterprises are from the European Union, US, and Japan, such as EU-based BASF, Novamont and Corbion, US-based NatureWorks and Metabolix, Japan-based Mitsubishi Chemical and Showa Denko. By capacity, BASF and NatureWorks top the list with respective capacities of 140 kt/a PBS and 140 kt/a PLA (Global and China Biodegradable Plastics Industry Report, 2014-2018, 2014).

²¹ Guyana for example has banned Styrofoam as of January 1, 2016 ("Guyana Bans Styrofoam Imports" 2016). Haiti has had two bans of Styrofoam, and is still plagued with related waste issues (Je 2013)

²² Chico bag, Ecobags, GreenBag to name just a few.

²³ Multiple projects in Ghana, Kenya, Honduras, Guatemala, Nicaragua and more

²⁴ BillerudKorsnas, and many more

Because of the lack of standards, these initial materials have created a substantial challenge for recyclers, consumer advocates, and the plastic industry alike.

According to European Bioplastics²⁵, a plastic material is defined as a bioplastic if it is either *biobased*, *biodegradable*, or features both properties, an extremely broad category. The term *biobased* means that the material or product is (partly) derived from biomass. *Biodegradation*, other hand, is a chemical process during which microorganisms that are available in the environment convert materials into natural substances such as water, carbon dioxide, and compost (artificial additives are not needed). The process of *biodegradation* depends on the surrounding environmental conditions (e.g. location or temperature), on the material, and on the application. The property of *biodegradation* does not depend on the resource basis of a material, but is rather linked to its chemical structure. In other words, *biobased plastics may or may not be biodegradable*.

Further confusion is presented by the appearance of so called *degradable* materials, often mistakenly categorized as *biodegradable*. Polymers that are designed to be *degradable* may fragment into smaller pieces or even residues invisible to the naked eye. While it is assumed that the breakdown products will eventually biodegrade, there is no data to document complete biodegradability within a reasonably short time period. Hence hydrophobic, high surface area plastic residues migrate into water and other compartments of the ecosystem. This microscopic plastic debris, present as granular or fiber-like fragments, steadily accumulate in the oceans. Marine animals consume microscopic bits of plastic, as seen in the digestive tract of fish and amphipods.

The fundamental standards for complete *biodegradation* under composting conditions are:

- Conversion to CO₂, water and biomass via microbial assimilation of the polymer material in powder, film, or granule form.
- Same rate of biodegradation as natural materials such as leaves, paper, grass, and food scraps.
- The resultant compost should not contain any toxic chemicals.

The lack of definition of bioplastic has allowed a great deal of ambiguity to enter this market. As “The New Plastics Economy” report, as well as the UNEP paper on the impact of microplastics to marine life point out, *bio-based*, *biodegradable* and *compostable* plastics are not the same.

Development and Promotion of Alternatives: Ideation to Realization

As a result of discussions with industry, consumer advocacy groups and innovators and review of literature, the authors have observed a list of emerging requirements for any innovation to conventional, fossil-fuel based plastic materials. These materials must be:

- Disposable or compostable without toxic residue;
- Made from bio-benign materials and sustainably derived feedstocks that do not compromise human food sources;

²⁵ <http://www.european-bioplastics.org/bioplastics/>

- Manufactured as “drop-in”²⁶ and without generating toxic residue at any point of its manufacture;
- Non-toxic and safe (esp. if a toy, or food and beverage container, or comes into contact with human body);
- Price-competitive to manufacturers, which will allow them to keep consumer pricing down
- With all desirable properties of plastic for weight, moisture and gas barrier, etc.

While no one material is able to satisfy all of these requirements, there is a wide array of new, bio-benign materials for different applications that can meet these requirements, from edible food packaging to mulchable and compostable agricultural sheets, to compostable plastic derived from methane or agricultural waste.

The Path to Innovation

Thinking outside the box (framed by the conventional petroleum-based material), it is important to identify a path to innovations that could meet these requirements, as well as economic instruments that could de-risk and/or encourage investments in key areas that would expand these innovations.

A pragmatic approach would be to identify and prioritize the basic industry requirements, by target market and / or segment (*e.g.* non-toxicity, cost-effectiveness, non-threatening to food security), and then identify innovations that can address specific performance requirements. Prioritization must be made on the basis of economic, environmental and socio-economic benefits, and price / performance of the resulting material, with a clear understanding of the acceptable tradeoffs.

This basic approach will offer guidance to innovators and entrepreneurs and help them focus their efforts on the high-priority and high-value problems.

In search of the most complete lens for assessment of these new materials, the Green Chemistry approach, discussed further, has presented the most complete guidance to evaluating all aspects of material innovation. Beyond that, a key consideration also is market viability, i.e. how long might it take to produce a viable market alternative with the described price-performance properties.

For example, an **ideal** solution incorporates all features – derived from a renewable feedstock, with a sustainable end of life (designed for reuse or disposability), that incorporates or leaches no toxic additives and is economically viable and designed for complete bio-degradation.

The table below represents an example of an evaluation matrix that helps identify acceptable trade-offs.

Feature	Ideal	MVP 1	MVP 2	MVP 3
Sustainable feedstock	x	x	x	x
Sustainable end of life (disposability)	x	x	x	
Non-toxic additives	x			
Economic viability (cost of manufacturing)	x	x	x	x
Design for bio-degradation	x	x		

²⁶ EMF terminology, used to describe a material that can readily be used in existing manufacturing infrastructure

To examine the alternatives, we have borrowed an approach favored by the entrepreneurial community— defining the Minimum Viable Product (MVP). MVP is a term used by entrepreneurs to describe a product prototype with the highest return on investment versus risk. It is the “sweet spot” between products without all required features that fail at launch and the products with too many features that cut return and increase risk. Examining the MVP alternatives for new materials or products, one can identify areas where alternatives can bring an acceptable trade-off between features and performance, vs environmental impact.

A uniform requirement in all alternatives is their economic viability. Acceptable tradeoffs are certain features, which require a limited or dedicated set of commercial applications.

Minimum Viable Prototype 1

Closest to the ideal version, but still using additives that might leach toxic chemicals. This reflects the current state of innovation. Such material can be used widely except for food and beverage packaging. This is a material or a product that is derived from a sustainable feedstock, is designed for sustainable end of life, is economically viable and designed for complete biodegradation. Such materials currently exist, in the form of PLA, and they have a limited use for certain applications.

Minimum Viable Prototype 2

This is a material or a product that is derived from a sustainable feedstock, is designed for sustainable end of life and is economically viable. It might contain plasticizer additives that are toxic and might not be designed for complete biodegradation. While clearly not a most attractive solution, this alternative at least reduces impact on fossil fuels as feedstock, and – collected properly – can be re-processed into a secondary valuable life.

Material innovation is only a start to a complete solution that incorporates materials, manufacturing, product design and end of life practices, all within the principles of the circular economy.

A Complete Solution: Materials – Manufacturing – Product Design –End-of-life

The current industry focus on end-of-life management must be enhanced with an aggressive, strong, upstream investment in developing new materials and alternatives that are competitive (or at least comparable) in price and performance to current conventional plastic, but without the downsides. A continuous wave of innovation will result in:

1. **New materials** - non-toxic, compostable in conventional, non-industrial conditions and without toxic residue, and truly biodegradable alternatives to conventional plastics, with comparable economic properties and performance characteristics. Example of such materials are natural bio-polymers that are found abundantly in nature and tend to be readily degradable because organisms have evolved enzymes to attack them;
2. **New manufacturing processes** that can handle high volume production for the new materials, including, for example, injection-molding and extrusion for pulp produced from biomass;

3. **New recycling processes** that can handle mixed recycling streams including compostables, biopolymers, bagasse and other emerging materials; and
4. **New product design** that conforms to the principles of “circular economy” and cradle-to-cradle design, eliminates toxicity and reduces the use of non-renewable resources.

Building the Innovation Eco-system

Activating such broad-based innovation means engineering an entire innovation eco-system, from identifying and incubating early stage innovations, to accelerating businesses, to investing and deploying products into the marketplace. This is a complex undertaking that begins with qualified, trained innovators – chemists, engineers, biologists, material experts, and others and a focused effort to direct their innovation efforts to the high-value problems, materials, and markets. It requires a commitment to generate, incubate, and accelerate hundreds of innovations.

It requires building and growing the investment network to support these innovations through their normal lifecycle, which includes fully equipped material innovation labs and development space. Such lab space can be often provided by incubators in exchange for equity stake as Illumina Accelerator (Illumina 2016), or as a grant, modeled on the California Science Institute (2016) and USDA’s Western Regional research center.

Supporting the Entrepreneur Community

Beyond competitions and awards and offering temporary lab space, supporting the entrepreneur community extends into directing business strategy and product design into the high value areas, where consumption is the highest and market failures are the greatest. Currently, such high value areas are disposable plastic products and packaging, plastic medical waste, microbeads, non-toxic plastic additives, and *plasticizers*, with market focus on food services, food packaging, retail, personal care products, construction, transportation, and agricultural plastic.

Accelerator services include basic business startup support, as well as understanding how to leverage consumer advocacy and NGO strategic partnerships since the advocacy effort is essentially building consumer demand for these new products and services.

In many of the developing countries, accelerating entrepreneurship extends into innovative uses of agricultural waste to produce alternatives to conventional plastic, and to encourage a useful after-life of plastic waste. Regional projects in Central America have demonstrated that a combination of policy restricting certain polluting disposable plastics (straws, bottles, bags) opens opportunities for entrepreneurs to engage in developing the alternatives, as well as to distribute the alternatives.

Building the Investment Eco-system

Impact investment will secure the flow of funding required for these innovations to succeed but, as impact investment is in itself new and emerging, it needs solid metrics for success. The main challenge that besets that sector is demonstrating tangible, sustainable social and environmental impacts and profitable return on investments. In its 2013 report, “Lessons in Building the Impact Investment Eco-system” Avina Americas states, “*Barring conceptual, methodological and other issues related to measuring impact, the definition of what success looks like remains nebulous*”. This still holds true and,

as the report continues, “...the death of successful investments reinforces the mutual exclusivity between social and financial investments, maintaining social contributions within the philanthropic realm, through corporate social responsibility or foundation initiatives.”

The investment eco-system for chemicals and alternatives to plastic is young and lacks metrics for return on investment and prior history for investment horizons.

Creating Metrics for Success

The triple bottom line (3BL) is a version of the business concept of “bottom line” that includes social and environmental results in addition to financial results. It is often referred to a 3P – Profits, People and Planet. As a business concept, it is a favorite of impact investments, yet it still lacks economic rigor and discipline in measuring the “People” and “Planet” dimensions.

Many B-Corp²⁷ businesses endeavor to measure their impact by assessing a 3BL metrics. For example, Chico Bag, a business dedicated to eliminating disposable plastic bags earned an environmental impact score in the top 10% of all Certified B Corporations on the B Impact Assessment, a comprehensive assessment of impact on workers, the community and the environment (B Corp 2016) Another example is Thread LLC, operating socially-responsible businesses in Honduras and Haiti, and producing “responsible fabric”. An example of how Thread LLC measure their economic performance is their annual report (Thread International 2015) and the summary of 2014 impact-at-a-glance (below.)



Figure 7. Thread International Annual Report (2014)

Innovative and Transformative Public Policies

Policies that ban and restrict the use of certain products and materials have opened entrepreneurial opportunities, as previously described.

²⁷ B-Corporation is a corporate structure partially recognized by some US state governments, where a corporation assumes the legal responsibility of considering its impact on society and the environment, in addition to profitability

However, the innovation ecosystem urgently needs economic policies that encourage and incentivize the development of alternative materials from sustainable or renewable feedstocks. A good example is the Renewable Fuel Standard, the US national policy that requires a certain volume of renewable fuel to replace or reduce the quantity of petroleum-based transportation fuel, heating oil, or jetfuel²⁸. Similarly, a policy that demands a certain amount of disposable plastics to be created from a sustainable feedstock would create great opportunity for innovation.

Furthermore, economic policies offering long term economic incentives to those who incorporate innovation will help offset some of the associated economic costs and also help bring down the price of products made from alternative materials. A typical example is NewGen Surgical, a business from the Think Beyond Plastic 2015 cohort who has developed an alternative to the plastic single-use suturing device used in hospitals. NewGen's innovation is made from paper pulp and reduces economic and environmental costs associated with incineration of plastic waste, yet still is fighting a difficult battle to enter hospitals because of their massive purchasing agreement with approved providers. NewGen needs their customers to receive an incentive for replacing plastic products with a paper-based and more sustainable alternative. This is still difficult to achieve and in the end, the purchasing decision is made based on purchasing budgets and cost, not on environmental priorities.

Finally, Dualles System Deutschland and the Green Dot program dates back to first German packaging regulations. [Der Grüne Punkt](#) was a system introduced by Germany's environment ministry in the early 1990s. It makes producers and suppliers take back used packaging and helped unleash a wave of innovations including new recycling infrastructures, reducing the amount of plastic used in bottles and other food packaging, and inspired creative ways to encourage consumer engagement. These types of regulations, currently advanced under the framework of Extended Producer Responsibility, can have a profound impact on creating a favorable condition for innovation.

Engaged Diverse Stakeholders

In addition to the innovators, investors and policy-makers, the innovation eco-system depends on the active participation of other stakeholders, such as industry, as well as civil society, consumer advocacy groups, and governments. The present great attention to plastic pollution is an excellent vehicle to raise awareness and build consumer demand for alternatives, which ultimately creates the market and the opportunity. A focused and coordinated effort between the stakeholders is of the essence, such as focus on specific products and market failures. The movement on plastic pollution has created some great success stories, such as eliminating plastic bags in countries around the world (Ecolife 2016), ban on microbeads in select locations, bans on Styrofoam packaging and even reducing plastic bottle usage. Civic engagement has created momentum, which was crowned with a policy reflecting the public interest and support.

Economic Viability

One of the greatest challenges is the undeniable low cost of crude oil and natural gas. Economic projections point to a continued availability of cheap oil and natural gas. In assessing the advantages of

²⁸The RFS originated with the Energy Policy Act of 2005 and was expanded and extended by the Energy Independence and Security Act of 2007 (EISA)

this cheap feedstock, society needs to take into consideration its overall toxic impact and produce a fully loaded Life Cycle Analysis for disposable plastic products.

The Chemical Footprint Project, although general, is useful in this effort, as it provides a tool for benchmarking companies as they select safer chemical alternatives (Chemical Footprint Project 2016). Another sector initiative is Zero Discharge of Hazardous Chemicals project, which specifies chemicals including some related to plastics that are specified for phase out on a timetable for an entire sector.

It is essential to characterize the overall footprint of the primary types of disposable plastic used in consumer goods and include the most common categories, such as PE---LD/PE---LLD, PE---HD, PP, PS, PVC, and PET. This top-down LCA must incorporate values for global production of plastic as well as emissions factors found in the peer-reviewed literature and life cycle assessment tools for diverse plastic products.

The model could be built with emissions factors from GREET and GaBi, using standard ISO14040 and 14044 approaches for lifecycle analysis. The functional unit of the LCA would be kgCO₂e/kg plastic, where CO₂e are based on IPCC factors. Information from the EPA WARM model will be used where appropriate and supplemented with information from the published literature. The following lifecycle phases must be evaluated (at a minimum):

1. Extraction, including feedstocks for plastic and co-products.
2. Production, including energy intensity and mix.
3. Transportation and use.
4. Collection for disposal or recycling, including modes such as heavy duty trucks, and shipping to China where most recycling infrastructure is located.
5. End-of-life, including landfilling (methane emissions with or without energy recovery), combustion/incineration for energy recovery, down-cycled products (displacing need for virgin plastic), and plastic lost at sea.

The Case for Green Chemistry Innovation

Green Chemistry and the Circular Economy

A transition from closed-loop systems towards a circular economy is inevitable, and indeed is the only path forward. As Nature magazine writes, “Landfill swallows much domestic and construction waste, where residual energy is lost and decomposition under anaerobic conditions creates a stream of problematic sub-waste, from the powerful greenhouse gas methane to leachable contaminants such as benzene. The United States sends 40% of its food to landfill and discards 70–80% of the 145 million tons of construction and demolition debris that it generates each year — even though much of the wood, metal and minerals is recyclable. In 2012, Europe sent almost half of its 2.3 billion ton of waste to landfill. And that is just stuff: up to 50% of industrial energy input becomes waste heat.”

Extending the useful life of products, retaining value, and designing out toxic substances is key to this new design. When it comes to plastics, this means de-coupling from fossil-fuel based feedstocks and using bio-benign materials designed for bio-degradation, and using non-toxic plastisizers.

Green Chemistry will enable the circular economy as it allows for the benign reuse of a material that is safe and designed for circularity. It is the only holistic, integrated, and systemic approach to addressing marine plastics that focuses on source reduction, pollution prevention, and reduction and elimination of the toxic impacts of materials.

The basic set of green chemistry engineering principles go beyond concerns over hazards from chemical toxicity and include energy conservation, waste reduction, and life cycle considerations such as the use of more sustainable or renewable feedstocks and designing for end of life.

Green chemistry is a different way of thinking about chemistry and chemical engineering (American Chemical Society 2016). Over the years, different principles have been proposed in thinking about the design, development, and implementation of chemical products and processes. These principles empower and encourage scientists and engineers to protect and benefit the economy, people, and the planet by finding creative and innovative ways to reduce waste, conserve energy, and discover replacements for hazardous substances. Developed by Paul Anastas and John Warner (1998: 30), the following Green Chemistry Principles outline what would make a greener chemical, process, or product.

Prevention	It is better to prevent waste than to treat or clean up waste after it has been created.
Atom Economy	Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product
Less Hazardous Chemical Syntheses	Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment
Designing Safer Chemicals	Chemical products should be designed to affect their desired function while minimizing their toxicity
Safer Solvents and Auxiliaries	The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used
Design for Energy Efficiency	Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure
Use of Renewable Feedstocks	A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable
Reduce Derivatives	Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste
Catalysis	Catalytic reagents (as selective as possible) are superior to stoichiometric reagents
Design for Degradation	Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
Real-time analysis for Pollution Prevention	Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances
Inherently Safer Chemistry for Accident Prevention	Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires

Among the characteristics that enable a process to be called greener, many are commonsense goals. For example, a greener chemical process avoids the use of materials such as chlorinated hydrocarbons that are slow to break down or difficult to dispose of. Using solvents that are more biodegradable is preferred. Similarly, a process that reduces overall waste that includes all inputs into the process such as solvents, raw materials, and process aids. In addition, a green chemical process uses less energy and produces fewer greenhouse gas emissions. The greenness of a process is summarized by a term called the “E-Factor” which measures the total amount of solvents, reagents, and consumables used in kilograms and divides it by the kilograms of final product produced.

According to US EPA (2016), Green Chemistry applies across the entire life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal. It is a philosophy that applies to all areas of chemistry, not to a single discipline. It applies innovative scientific solutions to real-world environmental problems, and prevents pollution at the molecular level. Adopting these design principles, the Green Chemistry approach will result in source reduction because it reduces the generation of pollution, but it will also reduce the toxic impacts of chemical products and processes on human health and the environment.

Developing Products and Technologies

For those who are creating and using green chemistry, the hierarchy looks like this:

- Source Reduction and Prevention of Chemical Hazards
- Designing chemical products to be *less hazardous to human health and the environment*
- Making chemical products from feedstocks, reagents, and solvents that are less hazardous to human health and the environment*
- Designing syntheses and other processes with reduced or even no chemical waste
- Designing syntheses and other processes that use less energy or less water
- Using feedstocks derived from annually renewable resources or from abundant waste
- Designing chemical products for reuse or recycling
- Reusing or recycling chemicals
- Treating chemicals to render them less hazardous before disposal
- Disposing of untreated chemicals safely and only if other options are not feasible

Synergistic Effect of Green Chemistry Innovation Approach

Adopting the Green Chemistry approach can have multiple synergistic benefits. Prevention of chemical hazards will result in positive impacts on public health and the biota. Reducing and eliminating the dependence on fossil fuels will result in savings in CO₂ and conservation of non-renewable resources. Leveraging agricultural waste and biomass will result in better waste mitigation and end of life management. All of these cumulatively will bring new jobs, new economic opportunities and investments in the future, not cleaning up the past.

To businesses, these innovations would enable consistent revenue growth, preserving profits and economic opportunities without slowing down consumption.

Innovation Search Focus

To enable Green Chemistry innovation for alternatives to conventional plastics, global Research and development needs to focus on several key areas, as described below.

Material innovations with focus on eliminating toxic leaching; biodegradability that fits within current recycling flow; real compostability; increased moisture barriers for food storage and presentation; innovative uses of agricultural waste and waste from lumber industry; novel uses of paper pulp, bagasse, nanomaterials such as bentonite²⁹, etc. Of special interest are additives (flexibilizers, plastisizers etc) that are non-toxic and can help organic products achieve the desired performance characteristics of plastic.

Manufacturing innovations, with focus on injection molding and extrusion for paper pulp and bagasse; scalable low-cost production of molded fiber; manufacturing alternatives to plastic film, etc;

Design innovations that focus on models for reuse and integrating the “circular economy” design principles, as well as design that reduces exposure to toxic chemicals and chemical leaching;

End of life innovations, with focus on waste-to-value innovations or breaking down plastic waste to non-toxic collectable and reusable matter

Green chemistry polymers must possess adequate **physical properties** which will enable them to replace today’s conventional plastics more adequately. These physical properties are, at a minimum: transparency, flexibility, compostability, moisture barrier, weight and to some extent, durability. Commercial ventures under way in the United States, India, Canada, Europe, and Japan indicate that such technological advances are possible.

Green chemistry polymers have to be **cost-competitive**. Today, commercially available biopolymers are often significantly more expensive than synthetic polymers. Currently, only starch competes with synthetic polymers in terms of cost. The costs of raw materials might be brought down by a growing industry, increased consumer demand and business pressures, and regulatory costs.

Overview of Current Material Innovations

Bio-catalysts Material Overview and Applications

The use of enzymes immediately pushes the process towards the goals of green chemistry, because enzymes can work from completely renewable feedstocks, are biodegradable, and can replace metals.

One technology that has become a central part of green chemistry is biocatalysis. The use of enzymes has immediate advantages in turning a chemical process "green." Enzymes are nature’s catalysts, present in every living organism to carry out a wide range of chemical reactions. As such, enzymes are completely biodegradable. In addition, because they are typically produced by fermentation from sugars, enzymes are truly renewable catalysts.

²⁹ Food grade clay nanoparticles that can be added to paper pulp and improve its performance, flexibility and transparency

Applications

Biocatalysis has many attractive features in the context of green chemistry, and its impact will continue to grow. As biofuel companies look for more profitable ways to exploit their technology expect bio-based routes to certain large volume specialty chemicals to be commercialized in the near future. Examples include 1,4-butanediol, succinic acid, glucaric acid, terpenes, and even isobutene.

Chemical companies are looking to biocatalysis to improve the sustainability of their manufacturing. Nowhere have enzymes had a larger impact recently than in the pharmaceutical industry. Many drug substances are difficult to synthesize, requiring multiple steps, large amounts of solvents, and extensive purifications. Using enzymes as catalysts can improve the purity and reduce the amount of organic solvent needed, resulting in a much greener overall manufacturing process.

The same advantages may be deployed in the manufacturing of plastic products³⁰.

Businesses in Production

DuPont's Sorona®

Over the past 200 years, DuPont has developed a number of advanced materials such as nylon, Lycra®, Kevlar®, and other household materials. Today, they are investigating the creation of biomaterials from renewable sources, rather than petroleum.

By using glucose derived from corn-starch as the basis for Bio-PDO™, a bio-based monomer, DuPont has created a renewably sourced ingredient for bio-based fibers like DuPont™ Sorona®, which is used in everyday products such as carpet and apparel and represents an interesting textile innovation. At the production facility, a micro-organism is added to the glucose. Five nine-story-tall fermentors are filled with the organism and glucose. The organism then excretes Bio-PDO™, forming a broth that is then separated and distilled. As Dupont claims, "it is proven that biomaterials can compete head-to-head with existing high-performance polymers such as nylon and polyester in the marketplace, by offering both performance and sustainability benefits at a competitive price."

Sorona® is an exciting step forward in the use of naturally occurring biopolymers and while it does not create a fully degradable product, it demonstrates a pathway to a future where this would be possible.

Bolt Threads

Recently financed synthetic biology company producing Engineered Silk™, a high performance fabric modeled on spider's silk. Bolt's silk is made primarily of sugar, water, salts, and yeast, which combined forms a liquid silk protein. Through a process called wet spinning, this liquid is spun into fiber, similar to

³⁰A good example of the impact of biocatalysis on pharmaceutical manufacturing is the recent announcement by pharmaceutical giant Pfizer about changes in its process for the production of *pregabalin*, the active ingredient in its \$3 billion per year drug Lyrica. In 2007 Pfizer replaced a classical chemical processing step with a more efficient enzymatic step. The result is a 90% reduction in solvent, used a 50% reduction in starting material needed, and commensurately large reactions in other reagents and chemical inputs. The *E-factor* (amount of waste) of the process was reduced from 86 to 9.

the way fibers like acrylic and rayon are made. Since launching out of stealth in 2015, Bolt Threads has attracted the interest of both new investors and partners, including Patagonia. Inspired by the super material, but which so far has not been successfully replicated to marketable quantities and working at the molecular level, Bolt Threads aims to transform the textiles market, turning renewable raw materials into products with outstanding properties that meet specific consumer needs. The company is now producing its protein at large scale, and is moving into yarn manufacturing (Bolt Threads, 2016).

MetaMixis

MetaMixis rapidly discovers novel enzymes for biologically producing chemicals and materials. By combining recent advances in synthetic biology and computation, the MetaMixis platform can accelerate the development of new biological manufacturing routes. Currently, MetaMixis is partnering with companies that are looking to break down existing bio-polymers, synthesize new ones, or add valuable properties to polymer waste streams.



Natural Polymers and Bio-polymers Material Overview and Applications

Bio-polymers are any polymers comprised of biological monomeric units. A natural biopolymer is a biopolymer that is assembled by an organism in the natural environment. Natural bio-polymers are assembled enzymatically, and are comprised of bond types that have been present in nature for a long time. This means that enzymes have likely evolved to depolymerize these molecules for various purposes, including biological recycling, energy production or communication. Dedicated efforts to discover new enzymes in the environment help understand both the natural breakdown and assembly of biopolymers.

Green chemistry innovation is focusing on polymers that come from waste agricultural and marine feedstocks, or are found abundantly in nature. These polymers are desirable feedstocks for the new generation of plastics. These are abundant natural resources that are constantly being replenished. This, in turn, could revitalize the rural economy, both agricultural and marine, by providing additional demand for currently underutilized land or low-valued biomass commodities.

Commonly used types of natural biopolymers are based on cellulose, starch, glucose, and oil. Specific techniques are then employed to convert these feedstocks into thermoplastic starch, polylactic acid (PLA), poly-3-hydroxybutyrate (PHB), polyamide 11, and biopolyethylene. Many of them deploy the use of microbial fermentation. These materials are described below.

Starch Material Overview and Applications

Thermoplastic starch accounts for about 50% -80% of the global bioplastics market (Janssen 2009). Innovative Industry.net describes starch as a polymer of hexacarbon monosaccharide D-glucose, abundant in corn seeds, potato tubers, and the roots and stems of other plants. Starch exists in the plant as granules and is often described by its plant source as cornstarch, potato starch, tapioca starch, and so on. Starch is processed by adding plasticizers such as glycerol, propylene glycol, glucose, sorbitol, and others. To improve the mechanical properties of TPS-based materials, other additives can also be applied. These include emulsifiers, cellulose, plant fibers, bark, kaolin, pectin, and others.

Thermoplastic starch (TPS) is just one component of which starch based bioplastics are formed. The second part of the blend consists of water repellent and biologically degradable polymers like polyester, polyesteramids, polyesterurethanes or polyvinylalcohols. Throughout the melting process, the water soluble, dispersed starch phase and the water-insoluble plastic are bond together to form a waterproof starch plastic.

TPS is a renewable and flexible material that can be easily used in different thermoplastification processes with a standard equipment used in manufacturing synthetic polymers – this process is commonly referred to as “drop-ins”. These processes include injection molding, extrusion blow molding, injection compression molding, and extrusion. High-amylose corn starch (HACS) can produce films with higher barrier properties and physical strength than films made from a normal corn starch. Addition of plant fibers to TPS increases the mechanical strength and improves form stability by decreasing shrinkage of the material through the release of internal stresses. Thus, biocomposites (Chang, 2013) based on matrixes made from biodegradable polymers with reinforcement by natural fibers, such as TPS with flax, have great potential as packaging materials (Norma E . Marcovich, 2015).

Applications

Applications of thermoplastic starch include bags, yogurt tubs, cups, plant pots, cutlery, diaper foil, coated paper and cardboard. Most of the starch derives from crops such as potatoes or corn³¹.

TPS is biodegradable, costs 10% less than fossil fuel-based polymers (Janssen 2009, Jain *et al.* 2010, Keshavarz and Roy 2010, Chen 2010), it is non-toxic, and is derived from renewable resources. One of the disadvantages of TPS is its brittleness. During storage, this brittleness increases because of retrogradation. Retrogradation is the change in mechanical properties of TPS caused by the recrystallization process. In addition, TPS is not moisture or heat resistant, is gas permeable and has a relatively short shelf life. Thus, TPS is not suitable for food and beverage packaging. Of great concern is the fact that TPS is often used as a filler in fossil fuel-based plastics, and degradation of these composites results in the formation of microplastics.

PolyHydroxyAlkanoates (PHA) Material Overview and Applications

Polyhydroxyalkanoates (PHA) are naturally occurring biopolymers. They are a family of biopolyesters with diverse structures and are completely synthesized by microorganisms (Jain *et al.* 2010, Keshavarz and Roy 2010). PHA can be synthesized by over 30% of soil-inhabiting bacteria. Many bacteria in activated sludge, in the oceans, and in extreme environments are also capable of synthesizing PHA. PHAs are biosynthesized by a wide range of Gram-positive and Gram-negative bacteria as intracellular carbon and energy storage compounds. In most cases, they are produced and accumulated under stressed conditions such as nitrogen, phosphorous, or oxygen limitation in the presence of excess carbon sources. Some bacteria are capable of producing PHA as much as 90% (w/w) of dry cell weight during depletion of essential nutrients (Chen 2010).

³¹ Which is a problem and not desirable since it would adversely impact food supply

PHAs are composed of R(-)-3-hydroxyalkanoic acid monomers ranging from 3 to 14 carbon atoms with a variety of saturated or unsaturated and straight or branched chains containing aliphatic or aromatic side groups. Presently, more than 150 PHA monomers have been identified, leading to a wide range of co-polyesters differing in their physical properties. Depending on the types of carbon sources available and the biochemical pathways operating in the cell, microorganisms are capable of synthesizing various types of PHAs.

The cost of raw materials for PHA production plays a crucial role for the economics of a PHA production process. In an aerobic process for production of a bulk chemical such as PHA, roughly 50% of the production costs originate from the costs for the carbon source used. PHA can be produced from inexpensive renewable resources such as starch, agricultural waste, fiber wastes from the paper industry, plant and animal waste, food waste, and methane, thus greatly reducing the cost of production.

Applications

Most PHAs are thermoplastics and can be thermally processed using existing technologies in the plastics industry (i.e. “drop-ins”). The properties of PHAs can also be tailored to suit numerous applications ranging from stiff packaging goods to highly elastic materials for coatings. They show good barrier properties against oxygen, water, and oil. PHAs were initially used to make everyday consumer goods such as shampoo bottles and packaging materials by Wella (Germany). PHAs were also developed as packaging films mainly for uses as shopping bags, containers, cups, lids, and paper coatings, as well as disposable items such as razors, utensils, diapers, feminine hygiene products, cosmetic containers, medical surgical garments, upholstery, and carpets by Procter & Gamble, Biomers, Metabolix, and several other companies. Due to their low toxicity and biodegradability, PHAs have been widely used for high value-end products such as medical devices, medical implants, and drug delivery carriers.

The most important quality that set PHAs apart from conventional plastics is their complete biodegradability in the natural environment. PHAs are biodegradable under aerobic and anaerobic conditions. PHA is degraded in the environment by enzymes known as PHA depolymerases. Various bacterial and fungal species have been reported which degrades PHA extracellularly such as aerobic and anaerobic PHA degrading microorganisms isolated from various ecosystems such as soil (*Pseudomonas lemoignei*), compost, aerobic and anaerobic sewage sludge (*Alcaligenes faecalis*), fresh (*Comamonas testosteroni*) and marine water (*Pseudomonas stutzeri*), including deep sea, estuarine sediment, and air. Importantly, the degradation products of PHAs are non-toxic in nature. The degradation products are assimilated by microorganisms as nutrients, metabolized within cells, and transformed to carbon dioxide and water.

Businesses in Production

Full Cycle Bioplastics



Full Cycle Bioplastics (Full Cycle) turns organic waste into PHA. The FCB patent-pending technology is licensed to waste stream owners, such as waste haulers and food processors. The

licensee can then manufacture, with FCB's help, PHA on-site – successfully diverting greenhouse gas (GHG) generating organics from landfill and often reducing disposal costs. In a closed loop scenario, the PHA is processed into a product that the licensee can use in their operations. These products could be, for example, food packaging, pallets and rigid plastic packaging (RPCs), or compost bin liners. When the useful life of the product is over, the PHA product can be fed back into the manufacturing system to create new PHA.

FCB promotes circular economy benefits by unlocking value across multiple industries including waste processors and haulers, agricultural waste generators, plastic producers and converters, products companies using traditional plastic packaging or materials, and consumers that desire biodegradable products and green alternatives to traditional petroleum based plastics.

The FCB process exemplifies the principles of Green Chemistry. The process uses a mix of wild-type, non-GMO bacteria to both break down organic waste streams and build up the PHA polymer. FCB's innovations in PHA materials and manufacturing processes can be broken down into three steps:

1. A renewable feedstock, organic waste, is anaerobically fermented to produce a liquid effluent of solubilized volatile fatty acids (VFA). The unused fraction of this process goes to compost.
2. The VFA-rich liquid is fed to a consortium of hungry, mixed, wild type bacteria that consume the VFAs and convert them to PHA. PHA is an energy storage molecule, much like fat.
3. The PHA rich cells then undergo lysis and the PHA is separated, purified and made ready for commercial use. The solid waste fraction of this step also goes to compost and the liquid waste is very low biological oxygen demand (BOD) grey water.

This process is free of toxic solvents, surfactants and plasticizers. Enzymes can be used catalyze natural reactions occurring in the first and third steps.

PolyHydroxy Butyrate (PHB) Material Overview and Applications

Poly[R-3-hydroxybutyrate] (PHB) was the first type of PHA identified and is the most common PHA found in nature. PHB is an organelle in a microbe and is accumulated by many bacteria in response to the limitation of an essential nutrient [Varsha, 2011, Pachekoski, 2009]. It is used as internal storage of carbon and energy.

PHB was first discovered inside the cell bodies of microorganisms (*Bacillus megaterium*) that benefit the health of soil. As the energy storage mechanism of these bacteria, PHB is essential to the generation of healthy soil, a critical component of our natural environment. These microorganisms could not survive and keep our soil healthy without PHB.

As part of the naturally occurring carbon cycle, PHB is broken down by other microorganisms in a wide range of natural environments, including land, oceans and other waterways. It does not accumulate at any point in nature or the food chain. Furthermore, many studies have revealed that PHB can be used as an animal and fish food – not only as a source of carbon, but also as a pre-biotic, to enhance marine organism (shrimp, salmon, sturgeon, sea-bass) health.

The production of PHB is currently expanding. Companies worldwide, especially the South American sugar industry, can either begin production of PHB or enlarge their existing production capacity, which would most likely result in a price reduction to fewer than 5 € / kg (this would still be about 4 times the market price of polyethylene). PHB is distinguished from most other currently available biodegradable polymers primarily by its physical characteristics such as the insolubility in water and its resistance to hydrolytic degradation. It produces transparent film at a melting point of 175° C, and is biodegradable without residue. PHB is the most common type of a substance class termed polyhydroxyalkanoates, but also many other polymers of this polyester class are produced by a variety of organisms.

Applications

The application of PHB blends varies from the fabrication of glues to hard rubber. PHB was traditionally produced by bacteria processing glucose or starch, but in recent years many waste feedstocks (biogas, agricultural waste, volatile fatty acids, *etc.*) have been used. PHB has characteristics similar to those of the fossil crude oil derived plastic polypropylene, but with wide ranging biodegradability properties possible at end of life.

Businesses in Production

Mango Materials

Mango Materials produces a naturally occurring biopolymer from waste methane gas that is economically competitive with conventional, petroleum-based plastics.



In an energy efficient industrial process, Mango Materials produces polyhydroxyalkanoate (PHA), by harvesting renewable waste biogas that is normally flared or vented to the atmosphere. Mango Materials captures carbon from waste and prevents the release of methane.

Mango Materials enjoys a major economic advantage compared to competing PHA producers who have faced economic challenges bringing their material to market at a reasonable cost stemming from their continued use of expensive plant sugars as a feedstock. Mango Materials' innovation of using low cost, waste methane as a feedstock will reduce production costs and significantly drop the market price of PHA to a level finally competitive with conventional plastics.

Mango Materials develops strategic partnerships at both ends of its production process by engaging methane producers to source the carbon feedstock and potential end customers to introduce PHA into their products. Collaborating with methane generating facilities, such as wastewater treatment plants, landfills, and agricultural facilities, Mango Materials captures the synergistic benefits of shared infrastructure. Capitalizing on existing equipment, Mango Materials saves on heat, water, and electricity costs, while also reducing the energy and environmental costs of gas compression and transport. Mango Materials has a partnership with Silicon Valley Clean Water (SVCW), a wastewater treatment plant located in Redwood City, CA.

By adopting a decentralized production model, Mango Materials will co-locate its production facilities at the site of methane generation. A decentralized production model enables more efficiencies in the logistics and transportation of the product throughout the supply chain. Mango Materials has entered

discussions with the raw material suppliers of potential customers to supply PHA for various applications.

Cellulose Material Overview and Applications

Cellulose is the most abundant biopolymer on the planet and it is found in the cell walls of plant and bacterial cells. Cellulose is a high molecular weight, stereoregular, and linear polymer of repeating beta-D-glucopyranose units. It is the principal structural element and major constituents of the cell wall of trees and plants. The empirical formula for cellulose is $(C_6H_{10}O_5)_n$, where 'n' is degree of polymerization.

Cellulose acetate is a modified form of refined cellulose that can be isolated from biomass feedstocks and is made by reacting cellulose biomass with acetic anhydride and an acid catalyst. Cellulose acetate has good optical and packaging characteristics but is not as durable as other bioplastics. The thermoplastic cellulose acetate Bioceta is a transparent granulate processed at 170°C, and modified by addition of high amounts of liquid plant-based plasticizers to improve the complete biodegradability of acetylcellulose. Bioceta is slowly, but fully, biologically decomposed. Its forming can be accomplished by injection, pressing, or – in the case of film production – calendering or film blowing. Cellulose acetate films, however, possess relatively poor gas and moisture barrier properties and are known to undergo hydrolysis to produce acetic acid in what is commonly referred to as the “vinegar syndrome.” These properties have prevented more widespread use of cellulose acetate films in today’s food packaging applications.

Businesses in Production

Innovia Films

Produces the cellulose-based NatureFlex™ NVS line of films, which can be used for packaging of fresh foods. The film is made from wood pulp typically sourced from hard wood species such as eucalyptus and is transparent, antistatic, and semi permeable to moisture. In addition to being biodegradable, the film is also compostable.



Innovia states that the wood pulp originates from certified forests and they uphold the principles and standards laid down by the FSC® (Forest Stewardship Council)® and the PEFC (Programme for the Endorsement of Forest Certification). They hold both FSC® and PEFC Chain of custody certifications.

The manufacturing for NatureFlex™ is largely based on the process used for both Cellophane™ films and viscose fibres but the chemistry of the process was altered, this the resulting product is not 100% pure and completely biodegradable.

Nanocrystalline Cellulose (NCC) Overview and Applications

NCC is obtained from acid hydrolysis of cellulose fibers and represents a new class of nanomaterials. Compared to cellulose fibers, NCC possesses many advantages, such as nanoscale dimension, high specific strength and modulus, high surface area, unique optical properties, etc. The properties of NCC

depend on various factors, such as cellulose sources, reaction time and temperature, and types of acid used for hydrolysis. NCC can be used to make transparent films with favorable barrier properties. NCC can also be used to make aerogels or foams, either homogeneously or in composite formulations. NCC-based foams are being studied for packaging applications in order to replace polystyrene-based foams.

Businesses in Production

CelluForce



CelluForce is the world leader in the commercial production of CelluForce NCCTM a form of Cellulose NanoCrystals (CNC). Produced from the cellulose in trees, CNC is abundant, renewable and biodegradable.

The core properties of CelluForce NCCTM improve performance in materials such as: Oil and Gas, Paper and non-wovens, Plastics and Composites, Food and Beverage packaging and much more.

BillerudKorsnäs



BillerudKorsnäs AB is a Swedish pulp and paper manufacturer with headquarters in Solna. The company was established in 2012 as a fusion of competing firms Billerud AB and Korsnäs AB. The company is investing heavily in a strategy that embraces the use of nanocrystalline cellulose to improve the performance of paper pulp.

EcoXpac



The company is developing a “green fibre bottle” for Carlsberg Beer. The processes currently developed at ecoXpac are able to handle different sizes and shapes. The fibrous has unique mechanical and surface properties and is sourced from compounds that biodegrade in natural environments or are biologically inert as chalk and clays. The bottle will be able to enter a recycling cascade before returning to the source, not as waste but as a resource for the next generations.

Bagasse Overview and Applications

Bagasse is the fibrous material that remains after sugarcane or sorghum stalks are crushed to extract their juice. It is a waste product and typically burned in the fields. Bagasse can be molded into different shapes and products. Bagasse has a high heat tolerant and is moisture resistant, thus it is often used to produce utensils, cups and food storage containers. Bagasse products are biodegradable and compostable.

Businesses in Production

PulpWorks



PulpWorks Inc is the winner of multiple awards for excellence in packaging. PulpWorks offers compostable products, molded from 100% post-consumer waste paper and agriculture. Their environmentally thoughtful packaging is created utilizing the same technology that's been used for decades to create egg cartons.

PulpWorks offer a wide variety of colors, textures, and complexity.

PulpWorks patented *Karta-Pack™* is an excellent compostable, all paper and pulp-based alternative to plastic bister packaging. It is comprised of two pieces of compostable and biodegradable material – molded pulp and cardboard – that are connected to create a single package with the saleable article nestled safely in a cavity in the molded pulp component. *Karta-Pack™* is compliant with ISO 14000 and European Green Dot standards.

NewGen Surgical



NewGen Surgical, Inc. designs and manufactures sustainable medical devices and surgical products, an alternative to the current plastic disposable products used in hospitals world-wide. Through a process called Smart Sustainable Design™, single-use O.R. products are redesigned to offer sustainability, value, and performance. Their focus is on the millions single-use disposable O.R. products that end up in the landfill or get incinerated, creating unhealthy impacts in communities around the globe.

EcoPack

EPWS is a group of businesses, accelerator and municipals in a project to establish a production and



innovation of eco-packaging center in Israel with focus on innovation of production of pulp molding (Bagasse) for food grade products.

EPWS product assortment ranges from industrial ready-meal trays to everyday tableware such as plates, bowls, and trays – all of which can be made out of 100% paper pulp. Products are all food contact European Norm EN13432 compostable (some at HOME grade composting). Raw materials must hold the sufficient national/international environmental responsibility documentation such as ISO14000 to be able to work with us. Focus on delivering EN13432 materials along with close circle water and minimum surge waste production machinery systems.

Ecopack focus on the main pillars of innovation – design, new additives and nano-coatings, post process automation, and raw material to create groundbreaking synergy to truly introduce alternative to the current single use food ware.

Lignin Overview and Applications

Lignin is the second most abundant natural polymer on Earth and is a waste product of the pulp and paper industry. By using waste stream as a feedstock, it is possible to mitigate the impacts of landfilling lignin and to produce new materials that are biodegradable and non-toxic. Lignin is a natural antioxidant and UV inhibitor that can enable a more finely-tuned biodegradation of material at lower cost.

Innovative technologies currently in place enable businesses to produce lignin-based biodegradable alternatives to conventional plastic.

Businesses in Production

Grow Bioplastics

Grow Bioplastics have developed a family of innovative, high performance plastic and rubbers materials based on Lignin.



While they plan to produce several products including garbage bags, gardening containers and 3D printing resins, the key product strategy is to produce lignin-based, biodegradable mulch films for agricultural use. Leveraging the low price point of lignin, they can produce plastic resins for a price nearly equivalent in cost to PolyEthylene, the most common plastic used in the mulch industry. The resulting mulch films are price competitive to current bio-based mulch films and – unlike them - do not use food-based feedstocks. These new resins deliver a material with specified levels of biodegradability at a low cost, saving farmers valuable time and money.

MetaMixis



MetaMixis has a patented technology – an enzyme product that acts directly on lignin to enhance lignocellulosic biomass conversion. It has demonstrated compelling results at lab scale in terms of boosted conversion yields and hypothesized cost savings. Metamixis just began testing the first product with one of the global leaders in ethanol production. Their platform technology can produce an entire portfolio of products, enabling the entire bio-based economy (also currently in testing with one of the 100 largest global corporations).

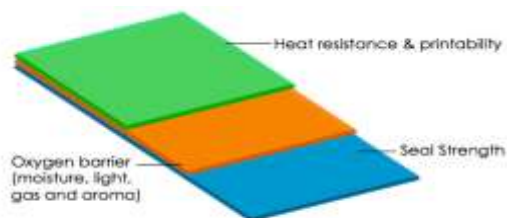
Compostable Film and Applications

The 2014 Report of the Flexible Packaging Association reports that the industry had US\$31.1 Billion in sales that year. This includes packaging for food, cosmetics, healthcare, and industrial applications. Squeezable / flexible packs are increasing in popularity within the food industry. The largest market for flexible packaging is food (retail and institutional), accounting for about 60 percent of shipments, which equates to about \$18.6 billion. Beyond condiment packets (ketchup, mustard, etc.), squeeze packs are used for baby food and adult snacks (Mamma Chia, GU). The flexible packaging industry has seen continual growth of 3.8% each year for the past decade. With flexible packaging growing in popularity, this market size is anticipated to continue to increase. In the US, packaging represents approximately 19 percent of the total \$164 billion U.S. packaging industry and is the second largest packaging segment. Growth in North America is primarily in specialty films, such as our compostable flexible film alternative. In 2014, the global plastic films market was US\$43.8 billion and is expected to grow at a CAGR of 8.7% to reach US\$85.6 billion by 2022. Asia-Pacific is leading this trend with more than 30% of the global market and China experiencing the fastest growth.

Packaging for single-serving high moisture foods is a continuous challenge. Single-use plastic packets for foods such as energy gels, peanut butter, and condiments today are neither recyclable nor compostable. Only few of the plastic film manufacturers carry compostable alternatives to petroleum-based plastic films for food packaging, including: EggPlant (still early stage), FKUR, Gualapack Group, Meredian, NatureWorks, Novomont, TianAn, Tipa and Tianjin. The leader by far in this area is Innovia, whose cello films division was acquired in April 2016 by Futamura Chemical. BASF is another go-to source for packaging converters seeking compostable materials for food packaging. Mitsubishi's "PBF" is new film

on the market. Although it is still partly made from petroleum feedstock, it is promising as an incrementally more sustainable alternative for packaging high-moisture foods.

In addition to these commercial initiatives, the Dibbiopack project in Europe (Dibbiopack, 2015) has conducted research into compostable films for high-moisture foods, including investigation into an O₂ sensor.



Plastic films for food packets typically have multiple layers, with each layer serving a distinctive purpose

The challenge in creating a compostable film is that the decomposition of the film is triggered by exposure to oxygen. However, the primary function of packaging is to prevent spoilage due to oxidation. Innovation in

compostable film will provide a superior oxygen and moisture barrier using compostable materials, and it will also prevent an oxygen breach. This distinctive combination of features will give users the added security of being able to tell whether the contents of the packet may be of degraded quality due to exposure to oxygen.

Emerging Businesses

NeuWorld Plastics



NeuWorld Plastics is developing a compostable film that can be used to make single-serve, branded packets for high-moisture foods like energy gels, ketchup, honey, and nut butters. This seed-stage startup is developing a film that can be composted right along with its food contents, eliminating the worry about sorting waste streams and about adding more plastic to landfills and waterways. Their film's unique

properties and signature oxygen barrier will allow producers and consumers to feel confident that the product they are using is safe as well as compostable.

Polyamide 11 (PA 11) Material Overview and Applications

A biopolymer derived from natural oil is polyamide 11 (PA 11). This polyamide bioplastic is also known under the trade name Rilsan. Although PA 11 derives from renewable resources (castor beans) it is not biodegradable and this, not a green chemistry innovation.

Applications

It is used in high-performance applications such as automotive fuel lines, pneumatic airbrake tubing, electrical anti-termite cable sheathing, oil and gas flexible pipes and control fluid umbilicals, sports shoes, electronic device components, and catheters.

Synthetic Bio-polymers Material Overview and Applications

Polyethylene (PE) material overview and applications

Polyethylene (PE) is generally known as a fossil-based polymer. However, it can also be synthesized from bioethanol (by dehydration) which is produced in large scale by fermentation of agricultural feedstocks such as sugar cane or corn. Bio-polyethylene is chemically and physically identical to traditional polyethylene – it does not biodegrade but can be recycled. It is not a green chemistry innovation.

Polylactic Acid (PLA) Material Overview and Applications

Polylactic acid (PLA) is a synthetic biopolymer, it does not occur naturally in the environment. It belongs to the family of aliphatic polyesters made from α -hydroxy acids, which include polyglycolic acid or polylactic. We are including a brief discussion on PLA here, as it is considered biodegradable and compostable, and frequently cited as a successful example of sustainable plastic alternative.

In fact, PLA has raised a number of serious concerns.

PLA breaks down into its constituent parts (carbon dioxide and water) within three months but requires a controlled composting environment, i.e. an industrial composting facility heated to 60°C and supplemented with digestive microbes. It will take far longer to degrade in a landfill where there is no light and little oxygen available to assist in the process. Another issue with PLA is that, because it is of different origin than regular plastic, it must be kept separate when recycled or it will contaminate the recycling stream. Another processing and product design challenge is presented by the PLA low melt point. Another downside of PLA is that it is typically made from corn or other feedstocks sourced from the food supply.

PLA cost of production is about 25% higher than conventional plastic. With the development of new and improved manufacturing methods, these costs will drop. As the cost of crude oil raises, PLA will become more cost-competitive.

Applications

PLA's characteristics resemble conventional fossil fuel based plastics such as polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET). It is easily processed on standard plastics equipment to yield molded parts, film, or fibers; manufacturing facilities that already exists for the production of common fossil fuel based plastics – no further industrial investments are required. The properties of PLA are suitable for a wide range of processing methods such as injection molding, film forming, blown-film, spinning, blow-molding, extrusion, and expansion molding. The potential areas of application for PLA include packaging and containers, agricultural and civil engineering materials, as well as composting materials. Because of the high transparency of PLA, it is an excellent material for packaging. Its blends have a wide range of applications including computer and mobile phone casings, biodegradable medical implants, foil, molds, tins, cups, bottles and packaging devices.

PLA and PLA copolymer plastics have already been used successfully for medical and pharmaceutical purposes such as the production of screws, nails, plates and implants that can be resorbed by the body. Also the use of PLA nanoparticles as drug carrier or MRI contrast agent is currently investigated.

Non-toxic Plastic Additives and Plastisizer Compounds

Interest among consumers and legislators in the safety and environmental impact of traditional *plasticizers*, flexibilizers and plastic additives is growing. Previously discussed in the section on Endocrine Disrupting Chemicals, these additives are often toxic to humans and marine life and are increasingly the cause for concern.

Even sustainably derived materials can result in toxic products that leach chemicals into human bodies or the environment. Increasing regulatory pressures and consumer education are prompting the innovators to search for safer and more sustainable solutions. Due in part to the ongoing industry debate over the safety and environmental impact of traditional compounds, some retailers and manufacturers of infant and children's items have voluntarily stopped carrying or using products made with these additives in response to pressure from consumers.

Businesses in Production

Vertellus

Vertellus is a specialty chemicals company focused on the manufacture of ingredients used in



pharmaceuticals, personal care, nutrition, agriculture, industrial and a host of other market areas affected by trends favoring sustainable technologies and chemistries. Vertellus is the largest, global producer of pyridine and picolines, specialty pyridine derivatives, DEET, castor oil derivatives and systems and a world leader in vitamin B3 and citrate polymer additives and systems.

A leading global supplier of additives to the plastics and polymer industries, Vertellus is delivering an entire line of bio-based, non-toxic Citroflex® plasticizers and Topanol® antioxidants that have a long history of safe use. Both high-performance additive product lines, they deliver low volatility and low leaching, making them suitable for a wide range of polymers used in food packaging, medical applications and children's toys. Vertellus' bio-based Citroflex plasticizers are derived from citric acid, which has been used safely in food for many years, and their Topanol antioxidants have earned broad approval in food contact applications.

In June of 2016, Vertellus filed for bankruptcy protection citing increased competition from China, legacy environmental and pension liabilities and capital structure and debt load. Their production continues, however.

PlastiPure

PlastiPure evaluates materials, packaging, and products to determine if they leach chemicals with



estrogenic activity (EA). PlastiPure uses its predictive models, large product database, and testing results from strategic partner CertiChem for this assessment.

If chemicals with EA are found to be leaching, PlastiPure works directly with material, packaging, and product manufacturers, using patented technologies to minimize or eliminate chemicals with EA leaching from their products.

Assessment of Material Innovation Potential

An assessment of these material innovations must necessarily include a comparison based on Green Chemistry compliance, economic viability, market viability, and potential to transform the marine plastics problem. A simple assessment done on a scale of 1-4, with 4 being the highest, is presented below. A more detailed material property comparison is offered in Appendix I:

- Green chemistry compliance - the number identifies how many of the 12 principles it meets;
- Economic viability – overall cost of manufacturing; expected price within 5-10% of the range of the current products. The expectation is that prices will drop with volume, and can be further impacted by favorable economic policy;
- Market viability – innovation tested in a small pilot and market-ready
- Commercial potential – innovation is applicable to a wide range of commercial products and will help solve a large scale plastic pollution problem
- Applications – wide or narrow, depending on features and conditions

Material	Green Chemistry	Economic Viability	Market viability	Commercial Potential	Applications
Naturally occurring biopolymers	****	**	**	****	**
Starches	****	**	****	**	**
Non-toxic additives	***	**	**	****	****
PHB (PHA)	***	***	***	***	**
Cellulose	****	**	**	**	***
Lignin	****	***	***	***	***
Compostable film	**	**	*	****	***

Waste Valuation Format for Rapid Assessment of Interventions

Understanding the nature of plastic waste and designing interventions with maximum economic impact and the lowest environmental footprint is one of the greatest challenges for municipalities dealing with waste.

To date, many of these interventions seek to invest in building or expanding recycling infrastructures, or to tap existing leakage points. These appear to be logical steps that would generate quick results, and in many cases that might be true. Often, little thought is given to the strategic, long-term investments that will address the plastic pollution root cause – the dependency on conventional fossil-fuel based feedstocks. Investing in strategically chosen alternatives with economic potential will secure the economic engine for a solution to the plastic waste problem, by creating forward looking jobs and economic opportunities.

The approach most suited to the complexity of this problem and its intended outcome incorporates basic design thinking with four key elements: (1) Define, understand and size the problem; (2) Create and consider a variety of options; Refine selections; (3) Repeat and Decide on a path; (4) Execute

While critical thinking is associated with breaking down of ideas, design thinking is a creative process based around the 'building up' of ideas, which encourages input and participation, eliminates fear of failure and often results in most creative solutions. Successfully implemented by business giants such as Deutsche Bank, General Electric, Procter & Gamble, Samsung and others, design thinking has demonstrated the capacity to bring original ideas, examine impacts and propel innovative thoughts.

A Waste Valuation Format designed following this approach embraces observation, iterative prototyping and analysis, it uses cross-functional teams and follows four key steps towards a solution roadmap, described below. The Waste Valuation itself is not a simple solid waste audit, although it incorporates data from existing waste audits, beach cleanups and municipal waste reporting; and incorporates and builds on inputs from NGOs, businesses, municipal waste authorities and others. It is an essential component of Step 1 of the design of the solution.

Step 1. Define, understand and size the problem

In this step, the focus must be on identifying the right problem to solve. It is essential to participate in defining the opportunity and to revise the opportunity before embarking on its creation and execution. Participation involves a team-based immersion, a “deep-dive” into the filters that have been employed to defining the problem and continuous examination. Defining the problem via design thinking requires the suspension of judgment in defining the problem statement. The goal of this stage is to determine the right problem and then to frame it in a way that invites creative solutions.

Unlike all current approaches that assume the plastic pollution is the result of insufficient recycling capacity, design thinking in this step helps observe the problem from many different angle before stating what it is.

With this in mind, in step 1 the focus is to identify the “hot-spots” of plastic pollution: site, business or activity where the market failure is the greatest, the need is most urgent, the pressure to act is the

greatest and currently no solutions are in place. Focus on environmental; public health; economic damages. Answer questions such as: Where is the plastic pollution generated; how much is it; what kind is it; why is it not stopped; what are the market and economic drivers; who has a vested interest in disrupting or maintaining the status-quo; what industries or businesses are impacted and others.

Successful examples of such analyses have helped define the following “hot spots”:

- **Islands:** because the space is limited and finite, resources and infrastructure is often non-existent and economic and public health damages are substantial. Exceptionally problematic are tourist destinations that combine impacts of tourism and plastic pollution. Example are the Honduras Bay islands, the Caribbean islands, the republic of Palau and others
- **Rivers:** because of the transboundary nature of rivers, often they become a very dramatic example of pollution, combining impact of huge consumption of plastic packaging, lack of infrastructure and lack of collaboration between territories where the rivers flow. Examples are: The Kabul River Watershed, The Montagua Watershed in Guatemala, the Yamuna river watershed and others.
- **Major tourist destinations**
- **Major public events:** concerts, public gatherings
- **Localized finite spaces, such as campuses (schools and universities, businesses etc)**

An example of a simple chart generated to support this analysis is below.

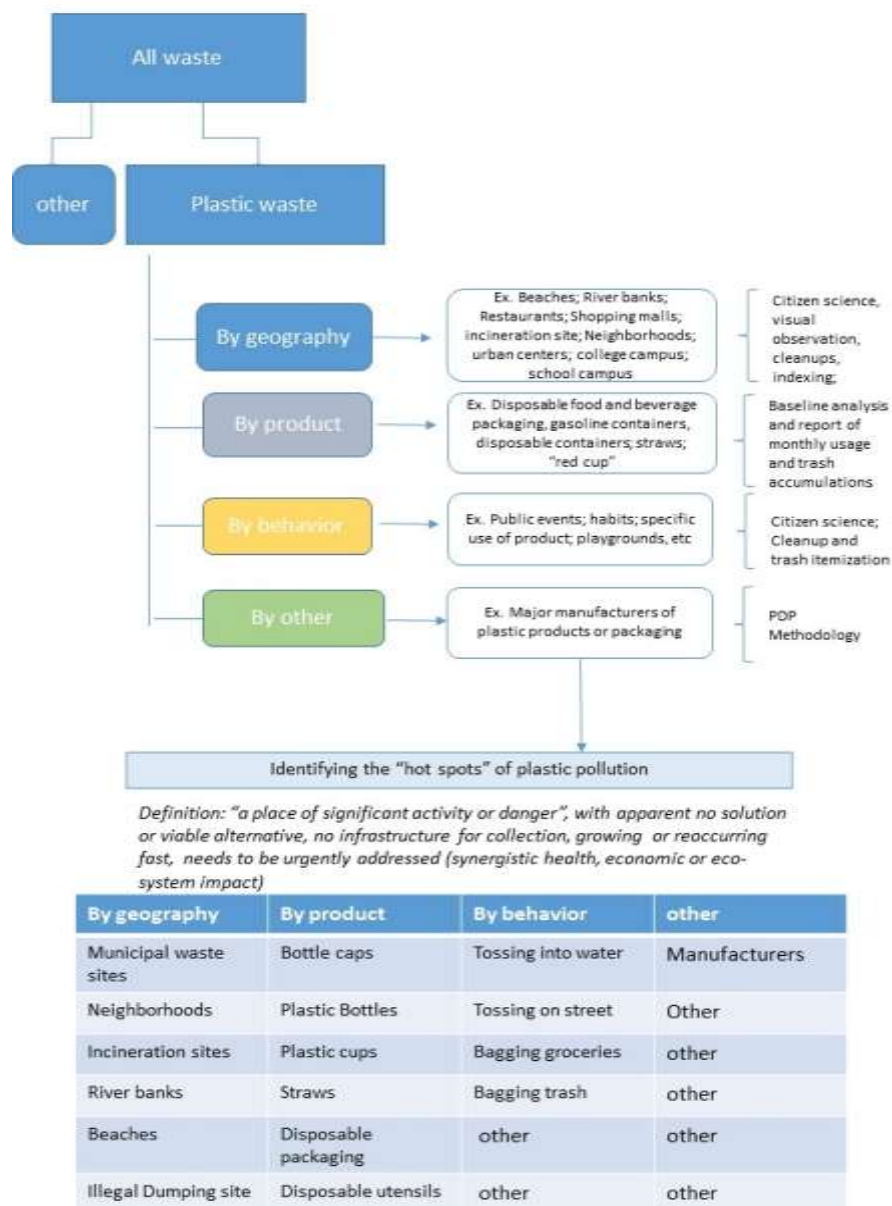


Figure 8. Identifying the Hot Spots of Plastic Pollution

Step 2. Size and estimate the range of solutions and/or innovations, tradeoffs and the required collaboration.

Design thinking helps avoid the trap of solving the problem the same way, each time. This has become a common practice with recycling, capturing and eliminating plastic waste, and deriving value from plastic trash have dominated the entire solution portfolio for years. Another common and repeated theme has been the inevitability of plastic trash.

In this phase, it is essential to consider a number of different alternatives with different potential interventions, their costs and implementation timelines and a set of other criteria that might be specific to the location and to the findings from Step 1.

Design thinking suggests that better answers happen when many people work on a problem for a day, than one person for many days, this bringing cross-functional team representing local interests is essential.

To generate richer results, in this step it is important to identify a range of available and appropriate *innovation opportunities* directly related to the measurable reduction of plastic pollution: material, manufacturing, recycling and design. Answer questions such as: Can alternate and/or local sustainable materials or products be used? Are they price-performance competitive? Will they create jobs?

The chart below represents the first step in this approach, to help navigate the portfolio of alternatives vis-à-vis their expected outcome. It is a high-level analysis to narrow down the expected impacts.

Step 3. Refine Interventions and Required Collaboration

One of the greatest advantages of design thinking is the environment conducive to experimentation and fresh review of ideas that might appear to have been previously considered.

At this stage, some ideas and suggestions might be combined and integrated into a synergistic whole.

Identify a range of *intervention opportunities* including existing supply chains, existing businesses and potential partners, target markets, opportunities for job creation and local entrepreneurship. Answer questions such as: Who / where are natural partners with investment potential? How can they be engaged in the process? What is the value of waste – negative and positive? Who are the entrepreneurs involved in this effort? Where are they? Do they need training and/or funding? And others

Examples	Investing Downstream <i>Managing impacts</i>	Investing Upstream <i>Prevent and redirect</i>
Policy	Ban on littering or illegal dumping Regulate emissions Ban incineration Control toxic residue	Ban on specific products; Tax incentives for developing the alternatives; Encourage local entrepreneurship; EPR
Material	End of life management Focus on waste management; investing in waste infrastructure; building excess capacity to anticipate increase in waste; substantial environmental impact (energy, toxicity)	Transform the waste stream New materials and products, using agricultural waste as feedstock; minimum fossil fuel depletion; minimal environmental impact; positive impact on waste
End of life	Recycling, incineration, waste-to-energy, waste-to-value Manage collection, separation and disposal of biodegradable and non-standard materials	Green chemistry alternatives: natural biopolymers extracted from agricultural mass or methane; composting, biodegradation in non-industrial conditions
Impacts	Jobs in recycling and waste management (low-skilled) Perverse incentive to generate more waste Continued investment in expanding infrastructure to meet growing consumption Major environmental footprint: toxicity and growing plastic waste	Jobs in green chemistry; professional training; new markets and new supply chains Cost savings in agricultural waste; incentive to find new markets for new products Self funded mechanism for managing waste streams Negligible environmental footprint
Urgency of action	Immediate results	12+ months results
Key Challenges	Managing growing consumption rates; Managing value of recycled material and incentives	Market volatility; Economics of commodities vs investment in alternatives

Figure 9. Refining Interventions and Collaborations

Step 4. Decide on a path and execute; Repeat

At this point it is the time to develop the plan to achieve the solutions that have been discussed and proposed. In the course of the process other unique ideas and strategies might have emerged. Prototypes of solutions are created and tested, in an intensive and critical fashion. At the end of stage 4 the roadmap to solutions is clearly described, and new solutions would emerge.

In this phase, elaborate on the preliminary assessment for success for the entire endeavor by key stakeholders: engaged and motivated government, active civil society and environmental community, iconic destination, the “low-hanging fruit” business opportunity. The ability to measure impact as simple ROI or double- or triple-bottom line is essential.

A simple map to solutions tailored to the specific “hot-spots” will contain analysis of the options, and the recommended and agreed upon next step.

Hot spot	Upstream	Downstream	Recommendation
Plastic bottle			
Plastic bottle cap			
Plastic bag			
Plastic straw			
Plastic cups			
Plastic utensils			
Plastic yogurt containers			
Plastic milk containers			

Figure 10. Decide on a Path

Advice to the GEF

(STAP to complete)

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Appendix I Properties of Biopolymers Comparison

Table 1. Physical Properties of Biopolymers

These tables compile key references on physical properties of the individual biopolymers.

Material	Properties							
	Transparent	Heat Resistance	Moisture Resistance	Gas Impermeable	Printable Surface	Film	Flexible	Rigid
Polylactic acid (PLA)	(1–3)	(4,5)	(6)	(7–9)	(1,5)	(10,11)	(12)	(13)
Poly-hydroxyalkanoates (PHAs)	(14)	(15)	(16,17)	(18)	(14)	(19,20)	(16)	(15)
Poly-hydroxybutyrate (PHB)	(21)	(21,23)	(24–26)	(27,28)	(21)	(29)	(30)	(30)
Nanocrystalline cellulose	(31)	(32)	(31,33)	(31,34,35)	(38)	(36,37)	(31)	(38)
Thermoplastic starch	(39)	(40)	(39,41)	(39)	(39)	(41)	(42,43)	(44,45)
Paper pulp	(46)	(47)	(48)	(48)	(48)	(48,49,50)	(51)	(51)
Bagasse	(52,53)	(54)	(55,56)	(57,58)	(59,60)	(61)	(62)	(63)

Table 2. Manufacturability of Biopolymers

These tables compile key references on manufacturability of the individual biopolymers.

Material	Manufacturing Process				
	Press Molding	Injection Molding	Extrusion	Sheet Processing	Thermal Embossing
Polylactic acid (PLA)	(64,65)	(66–70)	(71–74)	(75–77)	(78,79)
Polyhydroxyalkanoates (PHAs)	(80)	(81)	(82–84)	(85)	(86)
Polyhydroxybutyrate (PHB)	(87,88)	(89,90)	(91–94)	(95,96)	(97)
Nanocrystalline cellulose	(98,99)	(100,101)	(102,103)	(104)	(105)
Thermoplastic starch	(106–108)	(109–111)	(112–114)	(115–117)	(118)
Paper pulp	(119)	(120)	(121,122)	(123–125)	
Bagasse	(126–129)	(130–132)	(133–136)	(137,138)	

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Appendix II. Case Study: Innovative Intersectoral Policies

One start-up initiative in California, NeuWorld Plastics (NWP), is working on policy to address the problem of waste generated by condiment packaging. Their intersectoral solution is to combine a set of policies with the formation of a new private sector solution, a compostable alternative to the oil-based plastic films used to create single-serve packets for high-moisture foods such as condiments.

Market failures represented by condiment packets

Condiment packets produce too much plastic waste. There are several factors that make condiment packet waste an intractable problem:

- The product is highly profitable for the plastic film manufacturers, the packet distributors, and the food producers, so there is no economic incentive to stop making the packets.
- There is consumer pressure for retail food outlets in the U.S. to provide the packets at no charge (Graham, 2015).
- Since end consumers do not pay for the product directly, there is no incentive for them to exert pressure for change.
- Free distribution of packets leads to overdosing, as customers often take more than they need and retailers may distribute more than customers want in an effort to provide good customer service.
- No commercially viable compostable alternative to plastic packets has yet been developed that can be deployed at scale.
- Discarded packets have no reuse/monetary value, so there is no incentive for people to collect them [Unilever, 2013 & 2015].

Stakeholder landscape

In order to understand where to target policy, it is useful to have a picture of the stakeholder landscape. The condiment packet supply chain begins at an oil refinery, which produces the plastic pellets that are sold to plastic film manufacturers. Plastic film manufacturers sell rolls of film to packaging manufacturers who create food packaging for condiment producers. Food manufacturers typically outsource their packaging to third parties known as “copackers.” From there, packets are filled with product and distributed to food distributors and retailers who then sell or give away the product to end consumers.

Figure 1 shows a simplified stakeholder map.

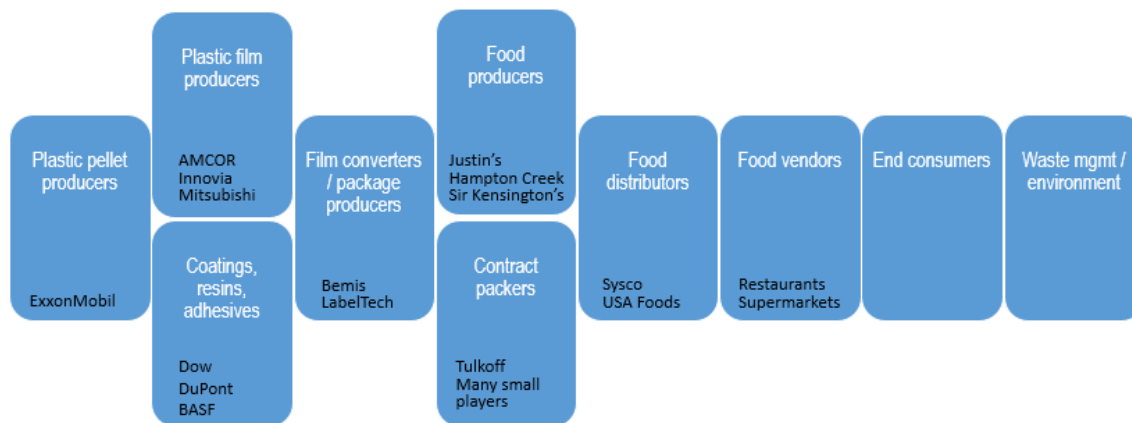


Figure 11: Supply Chain Stakeholders

Some stakeholders in the supply chain profit from the packets and some do not.

Profit

- Plastic film manufacturers
- Condiment packet distributors
- Condiment producers
- End consumer (retail food service customer)

Loss

- Environment (all living systems)

Mixture of profit and loss

- Retail food service vendors (restaurants, sports stadiums, theaters, theme parks, etc.)
 - Must pay for packets and distribute for free
 - *On the other hand:* Doing so wins customer satisfaction, sells more food
- Waste management/recycling services
 - Paid by weight, so profit from more waste
 - *On the other hand:* Limited space for landfill drives desire for less waste in long run and plastic film waste is so light that it doesn't significantly add to income under weight-based pricing models
 - *And:* For municipalities with waste reduction mandates, packet waste presents barrier to achieving goals.

Pending the development of an alternative compostable material with which to deliver single-serving condiments, and in the absence of a scalable solution for reusing, recycling, or upcycling discarded used packets, NWP is looking for ways in which policy can help frame a solution. Their plan would ideally apply at the state level but some policy case studies suggest that starting at the municipal level can be effective (Larsen and Venkova, 2014) (Parsons, 2015) (Siders, 2015) (Wade, 2015).

NWP calls for a multi-stage, multi-year program culminating in the ban of the oil-based packets, similar to the way plastic bag bans have been implemented in several U.S. cities and other countries (Alvey &

Noblitt, 2015). The elements of the plan are summarized in Table 1, which provides a summary of problems, market failures, and solutions.

- **Phase I:** Public education campaign on condiment packet waste, combined with a tax on distribution of packets that pays for R & D to find compostable alternatives to oil-based plastic packets.
- **Phase II:** Requirement that food retailers charge end users for the packets. Tax proceeds will be used to pay for grants to fund R & D into creating a compostable alternative to plastic packets.
- **Phase III:** With new, compostable material for condiment packets having been found, the state bans distribution of non-compostable packets. Retailers continue charging for packets, since this has now been established as the new normal. This covers the increased cost of compostable packets.

Problem	Market Failure	Policy changes
Pollution caused by packets	Negative externality; breakdown of environmental systems.	Progressive, multi-year plan to ban oil-based single-serve condiment packets
No alternative to plastic packets	Insufficient competition/Insufficient innovation.	Subsidize R & D for compostable packets or other alternative packaging through taxation.
Too many packets demanded/distributed	Moral hazard	Tax the distribution of packets
Packets are very profitable to manufacture & sell	Moral hazard	Tax manufacture of plastic film
Customer expectation of free product	Incomplete information/free rider/public good	Require info about effects of plastic waste./charge end user
No way to recycle or reuse the waste	Insufficient competition/innovation	Subsidize R & D for mechanisms to sort and/or repurpose the packets.**

Table 1: Summary of possible policies

**The NWP plan does not focus on recycling because recycling does not solve the problem of plastic waste being generated in the first place.

Their solution draws on two examples of legislation successfully enacted in the state of California:

1. **Senate Bill 270** (California Legislative Information, 2015) bans retail stores from providing single-use carryout plastic bags to their customers. Like the plastic bag ban, the challenge for banning condiment packets will be to provide a clear picture to consumers of the waste problem they represent, as well as providing compostable alternatives. “California cities enacting [plastic bag] bans commonly cite two main justifications: reducing unsightly street litter and protecting

marine life,” pointed out one reporter (Gabrielson, 2015). A similarly compelling story would need to be told about the harm that plastic waste from condiment packets causes.

2. **Berkeley, California’s 20% tax on the distribution of sugary drinks.** This example illustrates the effectiveness of a tax on distribution as a means for raising revenue:

“...the tax has brought in \$375,000 in the first quarter, and city officials estimate it will generate \$1.2 million this year. In June, the city council voted to commit \$500,000 of this to a reserve fund, with \$250,000 allocated to the Berkeley Unified School District Cooking and Gardening Program, which promotes sustainable nutrition and local produce. In October the Sugar Sweetened Beverage Panel of Experts recommended that \$200,000 be allocated to the Public Health Department for communication and education grant programs.” (Parsons, 2015)

Similar legislation failed in the city of San Francisco, where the proposal was to tax at the retail level (Siders, 2015). A successful policy will target the players who are furthest upstream in the supply chain, and provide pain relief for retailers for whom condiment packets are a cost of doing business. This is NWP’s rationale for imposing a tax on packets at the distribution level first and then at the retail level later, to provide relief to retailers by giving them a reason to charge for the packets and gain extra income. See also the very successful initiative in Mexico (Wade, 2015).

Measuring success

NWP plans to measure success based on how effective the plan is at reducing the number of non-compostable condiment packets purchased or distributed by retailers. They decided on this metric because measuring reduction of environmental waste is impractical when it comes to condiment packets, which are very small and hard to retrieve from the waste stream. There is also a significant delay in removing existing packets from the waste stream, as condiment packets are often stored for long periods of time in homes, offices, and schools due to their long shelf life.

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