MISTRA
The Swedish Foundation for
Strategic Environmental Research

Background paper

Plastics in a sustainable society

March 1 2015

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The contents of this background paper
are the responsibility of the authors.

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Content

Background 4

The Assignment 4

1 Introduction to Use of Plastics 5

1.1 Plastics consumption 6

1.2 Relevant Expertise in Sweden 8

2 Sustainable Use of Plastics 11

2.1 Four Focus Areas 12

3 Bio-based Plastics 15

3.1 Introduction 15

3.2 Plastic-Wood Combinations 17

4 Plastics in Marine and Freshwater Fnvironments 20

4.1 Impact on marine and freshwater environments 21

4.2 Microplastic and human consumer impacts 25

5 Focus Area 3: Consuming plastics 27

5.1 Measuring the sustainability of plastics consumption 27

5.2 Reducing absolute volumes of plastic consumption 28

5.3 Increasing rates of plastics recycling. 28

5.4 Shifting consumer perceptions and the cultural ‘values’ of plastic 29

5.5 Understanding the dynamics of everyday practices and the changing demand for plastics 30

6 Focus Area 4: Improving Plastics Waste Management 32

References 34

Background

A decision taken by the MISTRA board of directors in June 2014 identified "Plastics and the Environment" as an area for investigation with a view to initiating a call for research proposals in the future. The rationale behind this decision was that plastics have become an integral part of our society and lifestyle being prevalent in almost every aspect of our lives. However, despite the high societal benefits plastics evidently provide they also pose a number of environmental and health problems. Recent reports in the media, for instance, tell of additives with endocrine disrupting properties leaching out of plastics and entering the food chain and of plastic waste accumulating in huge quantities in marine environments.

The dilemma faced by society due to its reliance on plastics, in turn is also responsible for a depletion in non-renewable resources, places considerable and growing strain on the ecosystems and the environment. These issues must be addressed in terms of finding new sources of materials that are wholly or partially based on renewable resources, finding ways to increase the life cycle of plastics already in the material streams through re-use and recycling, eliminating the stream of plastics finding their way into the environment and eliminating or drastically reducing the levels of toxicity in plastics and additives.

Mistra envisages an interdisciplinary research program that will assess the current problems which accompanies the extensive use of plastic with a view to finding solutions leading to an overall reduction of the adverse environmental of plastics. The program should adopt an approach that takes a wide range of aspects into consideration including technical and process developments, patterns of consumption and environmental impact and consequences associated with implementation of new technologies.

The Assignment

A working group comprising international experts from different disciplines was convened and charged with the task of preparing a background document to be presented to Mistras' board of directors. This background document provides the board with sufficient information to make an informed decision regarding a possible call for research program proposals in this topic.

The tasks assigned to the group are:

- To describe the technical and societal challenges regarding the use of plastics
- To provide an overview of current research on the topic and to relate it to the state of research on the topic in Sweden.
- To identify gaps in current knowledge concerning plastics and the environment.
- To propose areas where a research program based in Sweden can make a significant contribution to the solution of the environmental problems associated with the widespread use of plastics.

The final report will be submitted to Mistra not later than March 6 2015.

1 Introduction to Use of Plastics

During its short history of only less than 75 yrs, plastics have emerged as the material of choice in a diverse variety of applications. The World production of plastics has been on the increase exponentially and in 2013 stood at 288 MMT of resin. In terms of global per-capita consumption during the last few decades, plastics clearly outperformed competing materials such as wood, metal or glass as a material of construction. There is a continuing trend of the substitution of these competing materials by plastics in building, packaging, construction and medical devices. The reason behind this impressive market success of plastics is attributed to its unique functionality and low cost. Plastics are relatively lower in density and can therefore be inexpensively transported, durable under most environments, bio-inert allowing it to be used in food-contact uses, formable into complex shapes, recyclable at low cost and are cost-effective in most applications. With increase in global population and greater per capita use in developing regions of the World, plastics as a material is destined to continue its impressive record of use into the foreseeable future.

While numerous chemical classes of families of plastics have been developed a majority of the plastics products in use are based on only 5-6 of these. Those families of plastics used in high-volume (referred to as the commodity thermoplastics) are as follows: polyethylenes [PE], polypropylenes [PP], polystyrenes [PS], poly (vinyl chloride) [PVC] and poly(ethylene terephthalate) [PET]. These are referred to as *thermoplastic* as they can be melted at high temperatures and reformed into different shapes, enabling them to be recycled with ease. Another group of plastics (that includes polyurethanes and epoxy resins for instance) are the *thermosets* that do not melt and are not re-formable on heating.

Commodity thermoplastics are converted into market products via several steps. The virgin plastic resins are manufactured primarily out of petroleum oil and natural gas feed stocks via polymerization processes. This yields the familiar plastic 'prils' the raw material for product fabricators. This resin is often mixed intimately with other chemicals or additives, to allow high-temperature processing without degradation and to impart the specific properties demanded by the final product. This 'compounding' step involves mixing the chemicals with the melted plastics followed by re-pelletization. The plastic compound is then fabricated into useful products using a range of processing techniques such as extrusion and injection molding. The products are distributed to users and enjoy useful lifetimes that can range from a few minutes (in case of a food-service product such as a foam cup) to several decades in case of building products (such as an underground sewer pipe.) The useful life of most plastics products end due to cosmetic changes in appearance or health concerns on re-use (for example with single-use food service products such as plates or cups.) These post-use plastics are either recovered for reprocessing (recycling) or incinerated for energy recovery. As shown in Figure 1 the each of these steps also have an environmental signature and require energy expenditure, solid waste generations as well as emissions into air or water.

The value chain that results in finished plastics products is therefore somewhat complex. The industry segments that support this materials flow are shown in the flow diagram in figure 1 where the compounder (mixing the additive into plastics) and the processor (molding useful products from this mix) are assumed to be the same operation; this is becoming increasingly common in plastics industry. Some specialized compounders, however, still do operate and ship the compounded resin to the processors. Both in Sweden and the rest of Europe there are companies engaged in plastics business – importing, manufacturing, distributing, selling, or exporting -- at all the points of the plastics value chain.

The resin manufacturing operation accounts for about 4% of the fossil fuel feedstock resources consumed globally while compounding and processing the material into products requires energy costs equivalent to about 4-5%. This ~8% of expenditure in energy and associated environmental cost of the externalities during their production, use and disposal, constitutes the societal cost of plastics as a material.

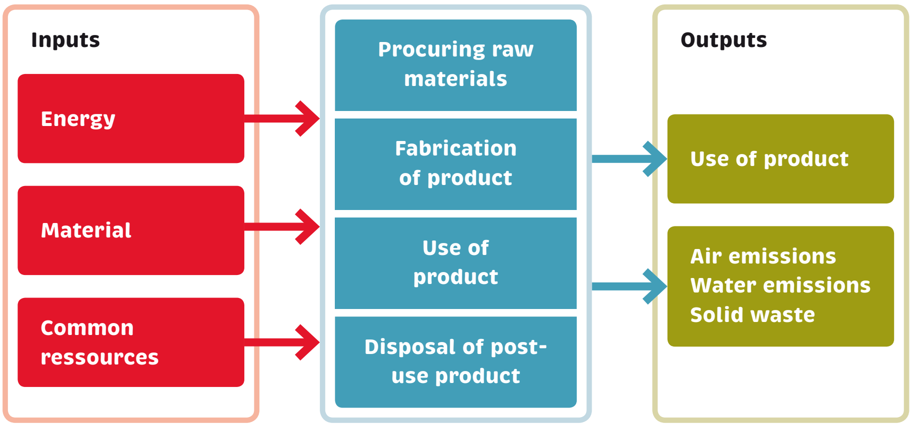


FIGURE 1. A schematic diagram of the steps involved in the manufacture of plastic products.

1.1 Plastics consumption

The rise of plastics is closely allied with the growth of consumer societies. Plastics, as components of goods and as goods in their own right, represent a comparatively cheap, malleable and durable material that has facilitated two critical features of an emergent consumer society: mass production of consumer goods at an unprecedented scale, and increased capacities for differentiation of products through their design. The demand for plastics has fuelled continuous innovation that has led to a global average annual rise in plastics manufacture and consumption of about 9% since 1950. Represented as per capita consumption this translates into 100 kg of plastics consumption per inhabitant in the NAFTA (North American Free Trade Agreement) countries and Western Europe, with predictions of reaching 140 kg per person by 2015 (OECD, 2010).

Within Europe, demand for plastics varies significantly by country (see Figure 2). Countries with larger populations, unsurprisingly, consume more plastics, while comparatively Belgium and Luxemburg, Italy, and Spain appear to consume higher volumes of plastics even when the population size is accounted for. Sweden appears on the lower end of the scale of demand for plastics.

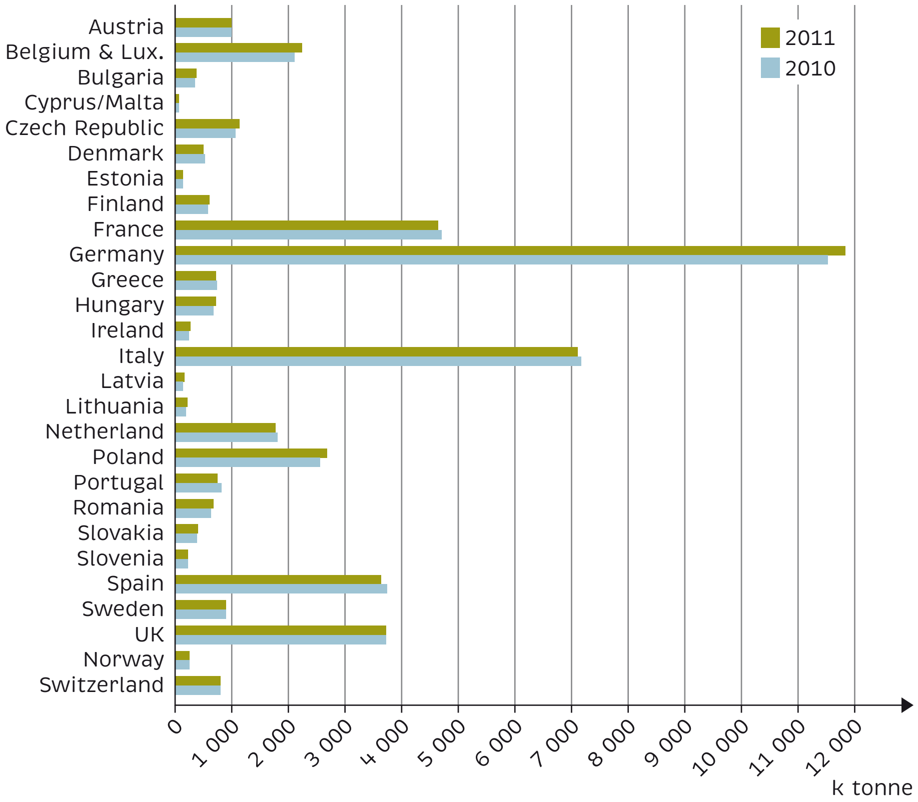


FIGURE 2. European Plastics Demand by Country, 2011.

SOURCE: PLASTICS EUROPE (2012. ORIGINAL DATA: PLASTICS EUROPE MARKET RESEARCH GROUP)

Given the wide variety of forms that plastics products can take, the material is ubiquitous within the consumer goods sector. According to Hopewell et al. (2009), approximately 50 per cent of plastic consumption takes the form of single-use disposable items (e.g. packaging and disposable consumer items), 20-25% relates to infrastructural applications (e.g. pipes, cable coatings and structural materials), and the rest are found in durable consumer applications (e.g. electronic goods, furniture, vehicles). Table 1 provides a basic breakdown of the European demand for plastics by application sector. Plastics touch a bewildering spectrum of forms of consumption, ranging from the food we eat through to the plumbing of our homes, leisure goods and the vehicles that facilitate our patterns of mobility. Yet, plastic consumption is largely inconspicuous and taken-for-granted in the course of consumers’ normal everyday lives. Consumers’ rarely think of plastics as a form of consumption: the demand for plastic is located in the demand for something else – for undamaged and longer life fresh foods, stylish car interiors and so on.

These statistics taken together indicate the exceptional societal benefits plastics provide. The diversity of application areas for plastics is illustrated in Table 1. Building and packaging industries has benefited most from this class of material. Plastics also help energy conservation (residential insulation) as well as energy production in cases such as wind-energy. Fraction of plastics in automobiles is on a

TABLE 1. European and US Plastics Demand by Sector, 2011.

SOURCE: PLASTICS EUROPE (2012. ORIGINAL DATA: PLASTICS EUROPE MARKET RESEARCH GROUP). US DATA FROM ‘PLASTIC RESINS IN THE US’, AMERICAN CHEMICAL COUNCIL PLASTICS DIVISION, JULY 2013

Sector	European Plastic demand (% by wt.)	US Plastics Demand (% by wt.)
Packaging	39.4	42
Building & construction	20.5	19
Automotive	8.3	5
Electrical & Electronic	5.4	3
Other	26.4	

slow increase whereas ocean-going vessel (the Visby) and aircraft (Boeing Dreamliner) has replaced main traditionally metal components of the design with plastic composites. Single-serve packages of food and medication would not have been possible if not for the availability of low-cost plastics.

However, the convenience of using plastics so liberally by the society has an associated environmental cost. Plastics production demands a small, but still significant fraction of non-renewable fossil fuels. Burning fossil fuel to power the plastics industry results in externalities including carbon emissions into the atmosphere. Even more of a concern is the potential for contamination of food and beverage by additives used in plastic products. Some of these are endocrine disruptor chemicals that can have adverse health effects at very low concentrations. The urban litter problem and the ocean plastic debris problem are also on the rise because of inadequate or ineffective post-consumer waste management. Addressing these environmental concerns of plastics use will require action to further reduce, re-use and re-cycle the plastic material to conserve fossil fuel feedstock. Material recycling of used plastics into other products (or even the same product) is a key strategy in conservation of fossil fuels and avoidance of externalities, and critical if ambitious environmental targets are to be met – not least EU targets for 50% of household plastics waste to be recycled or reused by 2020 (EU Waste Framework Directive). Doing so will additionally require a much better understanding of trajectories of demand for consumer goods (that use plastics), identification of where plastics can substitute for other materials (glass, wood, metals), and how consumers 'value' the different properties of plastics in products.

While consumers, especially in Sweden, are generally well disposed toward pro-environmental behavior, ready information and guidance on more sustainable product choices, opportunities for re-cycling, and the habituation of re-use practices could be improved significantly. There are significant market opportunities for consumer goods manufacturers and retailers to harness consumers environmental concerns by focusing on the potential for plastics use to become more sustainable. It will be essential for governments to exploit the potential of consumers

1.2 Relevant Expertise in Sweden

Success in the R&D programs envisioned here will invariably be measured in terms of innovations in sustainability science and consequent contributions to strengthening Swedish industry. Being a multi-disciplinary endeavor, the success of this effort hinges on achieving a broad national and international collaboration. Scientists in many developed and developing countries are studying patterns of use, disposal and recovery of plastics products in the society and their impact on human health and the environment. Interaction with this community can only support and facilitate this research effort. Within Sweden, however, the collaboration must include the academia, relevant industries and the government agencies. Industry has a wealth of practical experience that can be garnered in a research program on sustainable plastics.

For instance, consumer product companies including IKEA, Tetra Pak, H&M, and Electrolux, as well as organizations such as IKEM (the Innovative and Chemical Industries Organization), and Avfall Sverige, are relevant to the types of research envisioned here. Within the government, expertise on waste handling and recycling efforts exist within the Swedish Environmental Protection Agency, the Department of Energy, and other agencies. In addition, municipal governments in Lund and Helsingborg, in particular, have expertise developing and managing curbside recycling infrastructure.

1.2.1 Academic R&D Resources in Sweden

Within Sweden there is strong research and development expertise on these topics within academia, industry, and government. Sweden has a long tradition of quality academic research on plastics and this experience can be invaluable in pursuing advances environmentally sustainable plastics.

Table 2 lists the prominent academic institutes in Sweden with experience and strength in R&D relating to plastics materials.

TABLE 2. Expertise on Plastics in Swedish Academia

Institute	Areas of expertise
Chalmers University of Technology	Biopolymer technology
	Pharmaceutical technology
	Polymer technology
	Polymeric materials and nanocomposites
KTH The Royal Institute of Technology	Biocomposites
	Fibre technology
	Polymeric materials
	Polymer technology
	Wood chemistry and pulp technology
	Coating technology
Universty of Borås	Polymer technology
Uppsala University	Polymer chemistry
Luleå University of Technology	Polymeric composite materials
	Wood and biocomposites
Lund University	Polymer and materials chemistry
SP Technical Research Institute of Sweden	Polymer Technology
	Surface Technology
	Coating technology
	Materials technology
	Durability of polymeric materials
	Recycling of polymeric materials
	Polymer based nanocomposites
	Biocomposites
	Biotechnology
Swerea IVF	Polymeric materials
	Biocomposites
	Recycling of cable insulation and other plastics
	Polymer based nanocomposites
	Electrical conductivity of materials
Swerea KIMAB	Corrosion properties of polymers
Swerea SiCOMP	Polymer fiber composites
Wallenberg wood science center	Materials biorefinery
	New biopolymer concepts and surfaces
	Biocomposites
Inventia	Composites material

1.2.2 Working with other local resources.

Efforts at improved sustainability in industry are already showing impressive results worldwide. For example, the multinational beverage giant Coca Cola has launched the Plant Bottle initiative, and has been joined by other packaged goods firms such as Heinz in a quest to develop a 100% plant-based PET plastic. In Europe, packaging firm Tetra Pak unveiled its first 100% renewable carton made from bio-based low-density polyethylene (LDPE) films and bio-based high-density polyethylene (HDPE) caps, both derived from sugar cane, in addition to Forest Stewardship Council certified paperboard.

Relevant industrial interest also exists in the US. Stenungsund, in Western Sweden, is a hub of activity for R&D on sustainable plastics products, efficient production and developing renewable fuels. The chemicals and plastics firms AGA, Akzo Nobel, Borealis, INEOS, and Perstorp are cooperating to base manufacturing on renewable feedstock and energy and on upgraded recycled plastics by 2030. The firms have invested substantially in the development of more durable plastics for use in infrastructure and also a new recycling technology. For instance their R&D efforts enable tons of plastics used in power cables to be recycled and upgraded into other plastic products. The experience and innovative might of these industrial partners will be critical to Sweden's efforts to facilitate sustainable plastics.

Packaging consulting firm Smithers Pira Global forecasts the market for sustainable packaging to reach $244 billion by 2018. Demand will be driven by consumers' awareness of sustainability issues as well as legislative action, with food and beverage packaging likely seeing the greatest regulatory impact. The company points out that of all commodities recycled today, PET is the most valuable with a global market value of $2.9 billion. Representatives of IKEM, the Innovation and Chemical Industries organization, say that sustainable plastics is "an area of opportunity for Sweden because we have a lot of renewable raw materials and high skills in chemistry, biotechnology and life science".

2 Sustainable Use of Plastics

Sustainable growth is a fairly new concept to both the manufacturing industry as well as to consumers at large. A key aspect of overall sustainability of industry is environmental sustainability or the need to preserve the ecosystem services and non-renewable resources we enjoy in a relatively unaltered form for the benefit of future generations. In the existing paradigm, regulation is the primary means of ensuring environmental stewardship. But historically, industry has treated environmental regulations as a constraint, often an expensive one, limiting their growth. Multi-national players even relocate businesses to take advantage of the lax environmental regulations in different parts of the World. While the need to reduce the environmental footprint of manufacturing was always appreciated there was little incentive or a methodology as to the best way to achieve the goal.

The notion of sustainable growth first proposed at the Rio Conference in 1991 claimed that business growth (including expansion of manufacturing industry) could somehow be decoupled from its undesirable environmental footprint. It posited that while growth will be pursued for the benefit of the present society, a path exists to ensure the adequacy of resources (fuels, material and ecosystem services) for the future generations. The articulation of this vision or strategy of switching-over to this alternative way of conducting business is the domain of sustainable development.

It is critical that Sweden facilitate the coming regional transition of the plastics industry to sustainable growth from its exclusively profit-oriented growth. Being already a World leader in environmental stewardship and sustainability, this effort can result in high-value contributions to advancement of global sustainability in the use of plastics. It will also allow Sweden to set the standards to orient the consumer base, continuing its role of leadership in sustainable consumption. Even more importantly strategic adoption of sustainability research should facilitate the growth and competitiveness of the Swedish plastics industry in the coming decades.

This effort itself and the call for research that facilitates it can be readily justified.

a. Consumer demand drives the exponential growth of plastics use. Consumers are well known to be guided by 'environmental' merits of goods in making choices in the marketplace. Competitiveness of Swedish and regional goods in the medium term is likely to be influenced by these 'green' considerations.

b. Plastics supply chain interacts with regional and even global suppliers, fabricators and even waste recovery businesses. Some of these businesses are already adopting sustainable practices requiring the same from their partners, vendors and distributors. In Sweden where the plastics industry depends on imported raw materials and global exports of plastics goods, this effort can help harmonize global supply chain interactions.

c. Global markets are changing to business strategies based on sustainable growth and strategic positioning of Swedish manufacturing requires an outlook based on Sustainable growth. There are numerous first-mover advantages in evolving a 'responsible use' practice for plastics that includes the freedom to formulate ground-level standards and methodologies consistent with regional business practices.

Of the many facets of sustainable growth relevant to the plastics industry in general several focus areas that are consistent with the above criteria might be identified. Swedish industry is particularly well placed to exploit several of these areas to expand its plastics industry. Consistent with the considerations discussed above the panel recommends the following four areas for high priority R&D programs. These are summarized below and discussed in detail in subsequent sections.

2.1 Four Focus Areas

Focus Area 1: Using biomass in Plastics Industry

Research aimed at using the thriving forestry industry (~70% of Sweden is forests) and expertise in Sweden to make novel and sustainable plastics. As the demand for printing paper decreases in the paperless offices and mass media of the future, Swedish forestry industry will invariably have excess capacity in their wood and pulp production. Some of this excess capacity can be easily be diverted to plastics production. Two application areas show particular promise.

Area 1-A: Bio-based plastics.

Conservation of non-renewable feedstock is critical to sustainable growth of the plastics industry that now relies on feedstock of about ~5% of the fossil fuels used globally. As the volume of plastics produced grows in the next few decades' fossil-fuel demand will increase. Sustainable growth supports the use of renewable feedstock, mainly biomass as feedstock for the synthesis of plastics. The most salient of these are the new bio-based plastic resins that rely entirely or partially on biomass feedstock, thereby conserving non-renewable fossil fuels.

The research challenge in this area is to move away from biomass that are also food resources (such as corn) and seek ways to utilize waste or non-food biomass as feedstock for bio-refineries. This will require research that identifies new chemistries and processes that can be used with forestry biomass into bio-based feedstock for conventional or new classes of plastics. It also requires the discovery of new processes engineering pathways to scale up these new chemistries, to yield bio-based plastics.

Area 1-B: Novel and Improved Plastic-Wood Combinations

Wood powder is presently used as fillers in plastics to yield wood-plastics composites [WPCs] that are considered to be a more environmentally sustainable product compared to plastics. These are already used in outdoor civil engineering structures. However, the technology has room for improvement with potential to be developed much further to yield WPCs with higher mechanical performance and especially with improved outdoor durability.

A second category of product that has potential to be upgraded are plastic-infused wood materials. The existing technology where a monomer mix is absorbed into wood and then polymerized in-situ is available, but is unsafe and environmentally undesirable. Developing emission-controlled processes for this technology and exploring novel, hitherto not studied plastic-wood combinations are included in this focus area.

Focus area 2: Plastics in Regional Seas and Freshwater Ecosystems

Plastics pollution of the oceans and also freshwater ecosystems has been recognized as a serious ecological problem for several decades. The entanglement of marine life in plastics gear and packaging and the ingestion of small fragments of plastics by birds and other animals have been widely documented. A recent trend of microplastics accumulating in the World's oceans has been established. Microplastics present a particular concern as they concentrate water-borne pollutants and provide a pathway for these into the marine food web. There is a likelihood of microplastics even reaching the human consumer via commercial seafood.

Given the extensive Swedish coastline and a commercial fishery where 43% of the catch is for domestic consumption, keeping regional seas clean of microplastics should be a high priority. It is particularly important to ensure that the human consumers are not at risk because of the increasing presence of microplastics in the oceans.

The occurrence of microplastics in regional seas and in Sweden's coastal waters is well established. On the other hand very little information is available so far on the impact of microplastic in Sweden's freshwater lake ecosystems. To assess their impact or model their effects on the food web, however, data on ingestion rates, bioavailability of the pollutants in the microplastics and their transfer coefficients across the trophic levels need to be ascertained. As the data will be region-specific it is critical that this information is made available for at least the Baltic Sea areas.

The need to rule out any potential contamination of seafood by either microplastics or compounds leached out from these cannot be overemphasized. Particular attention must be given to the role of certain compounds (POPs and plastics additives) with potential activities as Endocrine Disruptors (EDCs). Given the local consumption levels and export of Swedish catch, this concern must be addressed urgently and unambiguously.

Focus Area 3: Consuming Plastics

While the demand for plastics use continues to rise understandings of this demand, and how its environmental implications can be reduced, remains limited. Existing studies that consider plastic consumption do so only as a secondary concern to other substantive topics (e.g. of recycling, product design and emergent consumer practices or goods). A step-change in understandings of plastics consumption is required in order to enhance the evidence base and inform public policy, business/industrial strategy, and consumer perceptions that includes the following core considerations:

- Systematic analysis (e.g. life-cycle assessments) of the environmental impacts of different plastics, viz a viz alternative materials, using measures that take full account of the social (e.g. use) and system level (e.g. accounting for shifts and 'knock-on' effects across product/ industrial sectors) dimensions of plastics production and consumption.
- Identification of opportunities and mechanisms for reducing the absolute volumes of plastics consumed, whether by encouraging consumers to reduce their consumption of plastics goods or by shifting from single to multiple use plastic products.
- Where plastic use is necessary or more sustainable than alternative material forms recycling rates need to be increased. Consumers, varying by socio-demographic, socio-economic and geographical constraints, have a crucial role to play in the disposal of plastic products.
- Understanding how consumers' value plastics in their consumption activities. Some plastics are synonymous with cheap and disposable materials (disposable razors) and contribute towards a 'throwaway culture', while higher quality plastics might have aesthetic properties that lead to a greater valuing of the material. Revealing the cultural meanings of plastics present opportunities to shift public perceptions in directions that can reduce the total volume of consumption, and increase recovery or re-use rates of the material.
- Analysis of the dynamics of everyday practices and how those changes generate more or less plastic consumption is critical if consumer demand is to be understood, anticipated and managed in directions that maximize sustainability outcomes.

Focus Area 4: Plastics Waste Management

Sweden ranks very high globally for its solid waste management performance with an impressive recycling infrastructure already in place. While Europe-wide the rate of plastics waste recovery is ~26% that for Sweden is already higher (~33%.) However, there is yet room for improvement, especially with respect to recovery and recycling of household plastics waste. A majority of the plastic waste in Sweden is used in energy recovery. From a sustainability standpoint, recycling is more desirable compared to incineration for energy recovery. There is value in identifying factors that limit the recycling of plastic waste and research strategies to address these.

To increase recycling rates, it will be necessary to assign additional responsibilities to one or more of the stakeholders. Stakeholders of sustainable plastics include product and packaging manufacturers, retailers, consumers, municipal governments, and waste/recycling companies and organizations. One model that has shown to be effective in Sweden is municipality-provided curbside recycling combined with materials sorting by consumers. But that model may not scale up easily from current rates or be cost-effective for less-dense population areas. Other models include material take-back programs at retail stores, neighborhood recycling centers, and single-stream recycling. The best approach or combination of approaches will vary depending on the community and financial resources, and should be selected after careful consideration of costs and benefits.

3 Bio-based Plastics

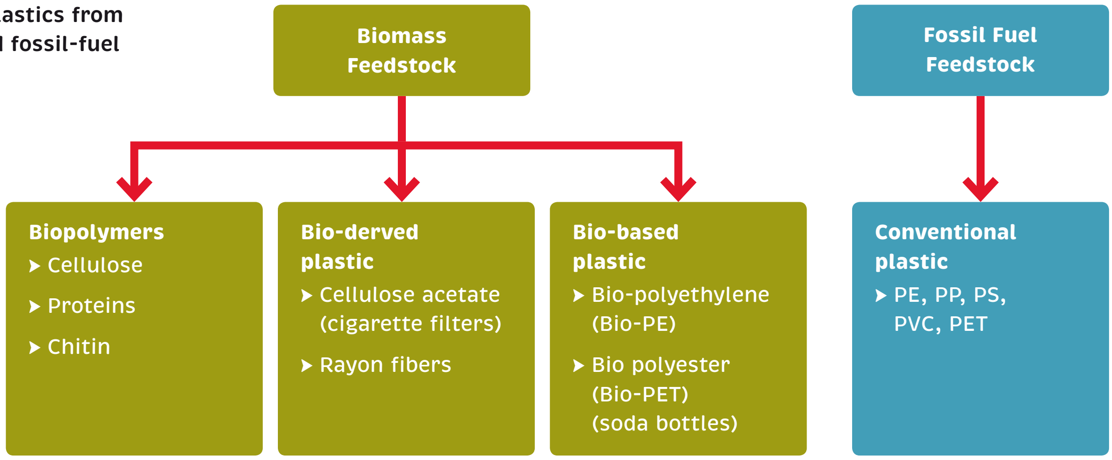
3.1 Introduction

With over 21 million ha of managed forest resources Sweden has a thriving wood and paper industry. It is the 2nd largest producer of pulp, paper and timber in the World, with the industry providing employment for over 20,000 people. In terms of worldwide deliveries of pulp or paper, Sweden ranks within the leading three nations (based on 2010 data.)

Plastics and chemicals producers look to renewable raw materials as a key strategy for producing future sustainable plastics. Only about 5% of each barrel of oil is currently used as raw materials for plastics and chemicals production. But fossil fuels are limited resources and the World is running out of these rapidly. Using renewable materials the industry can save fossil fuel resources, perhaps reduce the greenhouse gas emissions in the process and help regions comply with climate change initiatives. Commonly, the renewable raw material comes from plants: either purpose grown crops or agricultural waste materials. Other renewable sources that are under development are waste gases such as bio-methane from anaerobic digestion and carbon monoxide and carbon dioxide waste gases from industrial manufacturing. Replacing at least a part of conventional plastics in a product with their bio-based equivalent conserves energy and fossil fuel raw materials, and is therefore a sustainable move. Plastics associated with biomass feedstock can be divided into three groups as shown in figure 3.

Biopolymers are polymers produced by living organisms. Cellulose is the most abundant and most-used biopolymer used extensively in paper and cotton textiles. Bio-derived plastics are a second category consisting of modified biopolymers such as rayons where cellulose is re-processed and regenerated in a different form or chitosan made by chemically treating chitin from crab shells. Bio-derived polymers use a biopolymer as a raw material. Bio-based plastics, however, are a distinct class as they are man-made from small molecule building blocks (intermediates and monomers) made from biomass feedstock. The starting materials for the bio-based plastics on the market today are plant sugars, derived from sugar cane or

FIGURE 3: Plastics from biomass and fossil-fuel feedstock.



corn, or plant oils from soybeans or palm. In essence, those plant materials replace some or all of the petroleum in the manufacturing chain. The plant molecules can be converted into desired monomers and polymers via fermentation with bacteria or yeast, or through thermo-catalytic techniques. For instance, Corn might be fermented into alcohol that is converted to olefins to produce bio-polyolefins.

Environmentally biodegradable plastics are sometimes viewed as being more sustainable compared to their conventional counterparts, as they attempt to address the urban litter problem. There is a misconception that all biopolymers are biodegradable. Bio-based plastics may or may not be biodegradable depending on their chemical structure. Some bio-based plastics are biodegradable, including polylactic acid (PLA) resins, which is the most common biodegradable plastic on the market today. Others such as *b*-PE or *b*-PET are durable polymers similar to their conventional counterparts. Several biodegradable biopolymers (plastics) including poly(hydroxyalkanoate) (PHA) and poly(butylene succinate) (PBS) resins are also available commercially.

Figure 4 that summarizes the anticipated growth in bio-based plastics in 2018 illustrates the expected dramatic growth in *b*-PET resin (used in soda bottles.) Bio-based plastics are chemically identical to the fossil fuel derived analogues and have the same properties. These are therefore convenient 'drop-in' substitutes for the conventional plastic resins.

3.1.1 Biomass as feedstock for bio-based plastics

Products such as Corn are human food and scale up of the industry based on raw material that compete with food uses is impractical. A switch over to non-food sources of biomass, rather than starches, sugars, or food oils, is badly needed. Excess or waste biomass from wood and paper industries (as in the case of Sweden) or the use of agricultural wastes such as sugar cane bagasse, corn stover, wheat and rice straw, forestry residues, and palm processing wastes, would be ideal starting materials as they do not compete with food applications. Using local excess or waste biomass as feedstock will result in a sustainable source plastics, based on conventional life cycle analysis {LCA) calculations. In any event, using regionally available biomass resources that rely on existing supply chains is advantageous. It can reduce costs and create a less volatile price of raw materials, reduce market complexity, and even provide local employment

There is emerging regional interest in increased use of biomass as feedstock. In Finland, forest products firm UPM has opened a bio-refinery that makes diesel fuels from crude tall oil, a byproduct of pulp production. The renewable diesel fuel reduces greenhouse gases by up to 80% compared to the conventional diesel fuel. Chemical firm AkzoNobel and partners are investigating the potential to produce sustainable chemicals from sugar beets in northern Netherlands. In Italy, Beta Renewables has opened a cellulosic ethanol plant that uses wheat straw and a local purpose-grown energy crop called *Arundo donax*. Locally grown plastics is a newly established partnership in Sweden that includes 11 companies covering the entire manufacturing chain for bio-based plastics from the forest industry to the packing producers. SP Processum is the main project sponsor for this partnership.

Identifying available sources of these 'wastes' is not always easy. In the U.S., for example, farmers need to factor in measurements of soil fertility when deciding how much plant residue to collect from fields for cellulosic biofuels operations. Forestry industries in regions such as Canada, the Southeast U.S., and Northern Europe supply several downstream industries such as lumber, pulp and paper, and various heat, power and fuel operations. Indeed, several of the purpose grown non-food crops that have been proposed for biofuels and bio-based chemicals production can also be made into pellets for heating systems. The same may also be true of Sweden where wood and pulp resources are in plentiful supply. Therefore, firms looking to secure cheap, plentiful bio-based raw materials for making renewable plastics and chemicals may need to compete with other uses of so-called "waste" products.

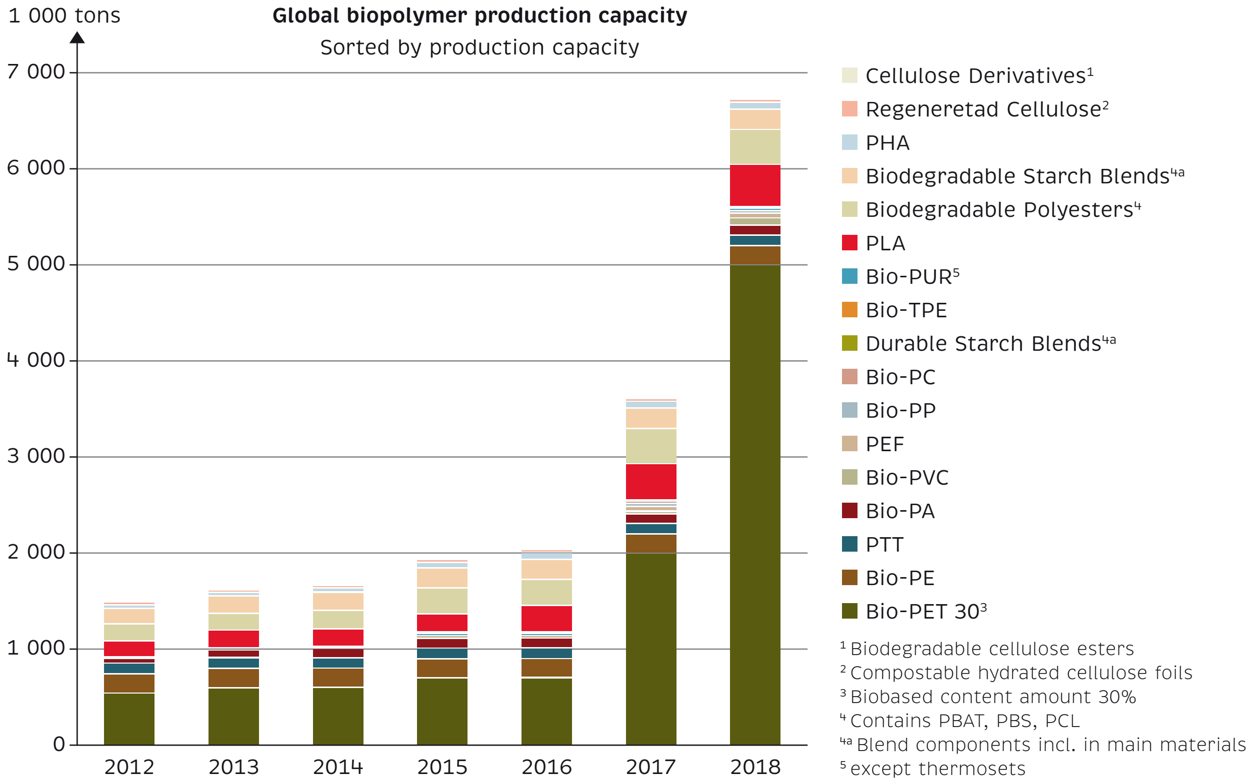


FIGURE 4. Projected growth in bio-based plastics in the medium term.

SOURCE: IFBB – INSTITUTE FOR BIOPLASTICS AND BIOCOMPOSITES

3.2 Plastic-Wood Combinations

3.2.1 Wood-Plastic Composites (WPC)

Wood and other materials derived from biomass have been used as inert fillers in plastics for decades. The use is not widespread or popular as the wood powder is usually not reinforcing filler in plastics and being a hydrophilic filler is not compatible with hydrophobic plastics. However, the recent interest in searching for sustainable materials of construction, with a lower environmental footprint (greener materials) is likely to make wood-plastics composites (WPCs) popular [Berge 2009], provided a few technological hurdles are overcome. In 2010 the global market for WPCs was 2.3 MMT but this is expected to grow at a rate of about 14% annually. Presently WPCs are used in civil engineering applications (bridges), in outdoor construction (decks) and outdoor furniture. Comparative lifetime analyses find the environmental footprint of wood to be generally superior to that of WPCs but the latter is superior to the use of 100 percent plastic materials.

Research aimed at identifying plastics/wood combinations that produce functionally superior WPC materials from biomass resources available in Sweden is identified as a key focus area of research. This includes not only the matching of wood species to plastics plastics to obtain a high-performance product but also developing improved engineering processes that can produce a new generation of WPCs economically while ensuring a low environmental footprint. WPC is also successfully manufactured using recycle thermoplastics and may present a particularly attractive recycling option for plastics waste in Sweden.

Technical hurdles that need to be addressed within this focus area include a) improving wood-polymer compatibility; b) controlling the engineering parameters (e.g. particle size distribution (PSD) of the wood filler used; and c) improving the outdoor durability of the material. While a literature on compatibilizers and surface treatment of wood powder exists, more work is needed and research on Swedish wood species is critical to success. A particularly interesting area of study might be the use of nanoscale wood fillers in plastics to obtain nano-WPCs. The PSD strongly influences the performance of WPCs but not enough information is available on the topic. Discerning the engineering parameters that lead to good performance in general and PSD-dependence of the performance composites for local biomass fillers in particular, would be a profitable research area. As most of the WPCs at present are used in outdoor applications, long-term durability is a particular concern. Work aimed at longer service lifetimes for WPCs based on local biomass would be a third research area of interest.

3.2.2 Novel Wood-Plastic Constructs

In addition to WPCs there can be other combinations of wood and plastics of commercial interest. An interesting variation for instance, is 'plastic-wood' technology. This material is made by polymerizing *in-situ,* selected monomers sorbed into the porosity of wood. The sorbed monomer is polymerized with a range of initiators such as gamma radiation, electron beam or thermally activated chemical initiators. The plastic component might be crosslinked *in situ* for additional stability and durability. The presence of plastic should dramatically improve the mechanical integrity as well as the weatherability of the wood.

While this type of process has been described in the literature (~1960s), the fundamental aspects of this process have never been researched sufficiently and the high cost of the product has prevented its popular adoption. However, the 'green' value of the product and its potential to convert softwood timber into a high-grade value-added material with superior properties makes this a promising topic for research in Sweden. Hitherto unexplored areas such as hybrid (inorganic organic hybrid) composites and foamed lightweight wood-plastic materials may hold promise as new generation materials. It is clearly an area where the Swedish expertise on wood science and plastics technology can work together synergistically.

Critical challenges relevant to this focus area are as follows.

Challenge 1.1: Developing new pulp-based chemistries that lead to monomers or other intermediates used in plastics resin manufacture.

Novel bio-refinery chemistries based on pulp or low-grade wood substrate to efficiently produce valuable intermediates in high yield is the core problem that needs to be addressed. These intermediates should be relevant to the synthesis of commodity plastics that are in demand in today's market and ideally be cost competitive with the fossil fuel based plastics. Initial R&D efforts should, however, be defined in terms of technical goals alone.

Challenge 1.2: Process engineering designs and innovations that allow the scale up of pulp-based bio-based plastics production.

Present-day practices in monomer production developed around the use of petroleum based feedstock. Switching over to bio-based feedstock will require rethinking these designs and the evolution of alternate processes that efficiently achieve the chemical transformations in an environmentally benign manner.

Challenge 1.3: Studies on improving the performance of conventional WPC materials by innovative control of the key process variables. Development of novel next-generation WPCs based on local biomass resources.

The WPC technology is still being advanced with initial products already in the marketplace for almost exclusively outdoor use. Developing cost-effective, more robust and durable WPC materials with improved properties will allow these to be used in higher-value applications. Researching the wood-plastic interface with the objective of improving compatibility and levels of reinforcement will allow for wider use of the 'green' WPCs based on Sweden's forest products.

Challenge 1.4: Using wood and plastics in novel configurations to design green, functionally superior class of materials.

Traditionally wood plastic configurations were limited to wood adhesive laminates (as with plywood), wood chip laminates and WPCs. Novel constructs based on wood and plastics need to be discovered as high-value materials. For instance, constructs based on wood nanofiber pulps or nano-powder plastics or polymer nanofibers in wood systems have not been developed.

Challenge 1.5: Investigate environmentally benign processes for polymerization of monomers within wood materials to yield novel plastic-wood material.

One of the drawbacks of the old 'plastic wood' technology is its unacceptably high environmental footprint. Research on improving the process to avoid emissions of monomer, reduce process waste while improving product quality can help develop an improved technology based on *in-situ* polymerized plastics in wood matrices. This research will have particular value in better using low-value softwood species in high-value applications.

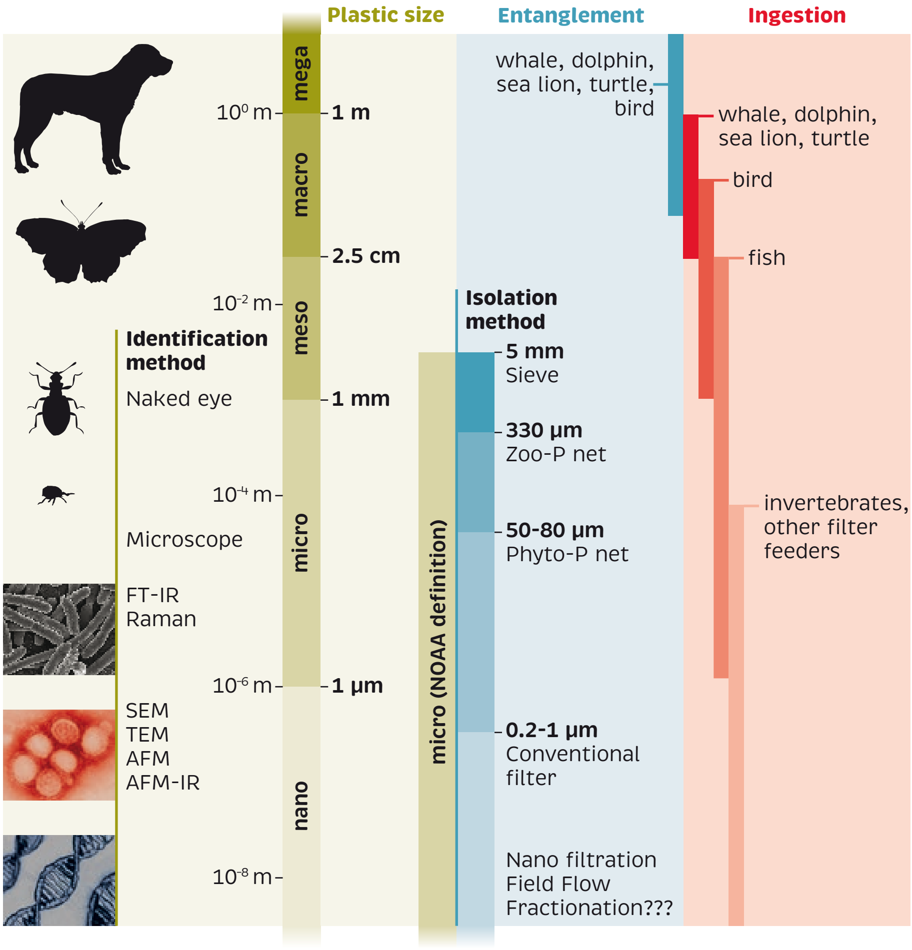
4 Plastics in Marine and Freshwater Environments

Sweden has over 13, 567 km of coastline with direct access to the North Sea and the Baltic Sea that is already under pollution stress. The country also has numerous islands as well. Clearly there is passage of agricultural waste (as evidenced by high eutrophication levels) at least into the Baltic Sea and the same is available for plastics pollution of the oceans. Plastics, especially microplastic litter, present an additional emerging threat to an already stressed marine environment in Sweden. Particular attention should also be given to the plastic pollution of the large Swedish freshwater lake ecosystems.

While plastics constitute only 10-13 wt% of the municipal waste they are the most important part of marine litter worldwide. One of plastics' crucial desirable properties, its durability, is also one of the main reasons that plastics present a threat to the marine environment. The risk increases as long as plastic continues to enter the ocean. Plastic enters seas from both land and water-based, diffuse

FIGURE 5. Classification, categorizes particles size into 'microplastics'. Particles in the size range 1 nm to < 5 mm were considered microplastics by GESAMP.

SOURCE: WWW.GESAMP.ORG



and point sources and can travel long distances before depositing on shores and seabeds.

Microplastics, defined as synthetic polymer particles ”< 5 mm” (Arthur *et al.*, 2009) which includes particles as small as 10 nanometres (GESAP 2014), are distributed throughout the ocean, occurring on shorelines, in surface waters and seabed sediments, from the Arctic to Antarctic. This broad category of ‘microplastics’ has been subdivided in a recent classification by GESAMP in 2014 (in ‘Microplastics in the Ocean. A Global Assessment’ *www.GESAMP.org*) As different size classes require different sample collection methodologies and affect different categories of marine biota this classification is particularly useful. The figure 5 below, based on the classification, categorizes particles of size n into ‘microplastics’ when 1micron> n <1mm; and ‘mesoplastics” where 1mm>n< 2.5 cm. By this definition, most of the studies in literature are on mesoplastics. Figure 5, Taken from the FAQs brochure of GESAMP (GESAMP 2014) illustrates this classification.

Plastic microdebris in the oceans may accumulate at remote locations such as mid-ocean gyres, as well as close to shipping routes, population centers, and other major sources of litter. Microplastics either enter the marine environment as pre-production pellets (primary microplastics) or emerge from the breakdown of larger items already present as marine litter in the oceans (secondary microplastics) through the combined action of mechanical, biological, photic and thermal abrasion, leading to their fragmentation into increasingly small pieces (Andrady, 2011; Cole *et al.*, 2011).

4.1 Impact on marine and freshwater environments

Scientific reports describing the occurrence of small plastic fragments in birds appeared in the 1960s and in plankton net samples in the early 1970s. However, the attention of the scientific community was aroused only about a decade ago to the significance of mesoplastic and microplastic debris in the oceans. Since then there has been an enormous increase in the number and diversity of publications on different aspects of microplastic distribution and behavior (Ivar do Sul *et al.* 2014).

The threats posed by plastic litter in the marine environment can be divided into three general categories: (a) ecological, (b) social, and (c) economic impacts (CIESM 2014). Ecological harm includes mortality or sub-lethal effects on organisms through unintentional captures from ghost nets, entanglement, physical damage and macro and microplastic ingestion. Uptake of microparticles may be connected with the release of associated chemicals, the facilitation of invasion by alien species, ingestion of microbes, and the alteration of benthic community structure. Social harm includes the reduction of recreational, aesthetic or educational values of areas such as beaches, as well as risks to human health and threat to navigation. Economic harm includes direct cost and loss of income due to marine litter affecting a range of maritime sectors including shipping, tourism, aquaculture, and fishery.

Despite the ubiquitous nature of plastic and microplastic pollution within the open water of oceans and seas, data describing microplastic abundance in freshwater ecosystems are very limited. Eriksen and colleagues (2013) reported the presence of plastic pollution in the Laurentian Great Lakes ecosystems, with overall counts varying from 0 to 450,000 microplastic per square kilometers. Faure and colleagues (2012) reported that macroplastic and microplastic have been found on the beaches and in the surface layer of Lake of Geneva in significant quantities. They represent a potential credible mechanism for input of absorbed pollutants or plastic additives into the freshwater food chain and these toxic chemicals may potentially reach the human consumer as well. Figure 6 shows the wide geographic distribution of marine microplastic debris (Ivar do sul et al 2014).

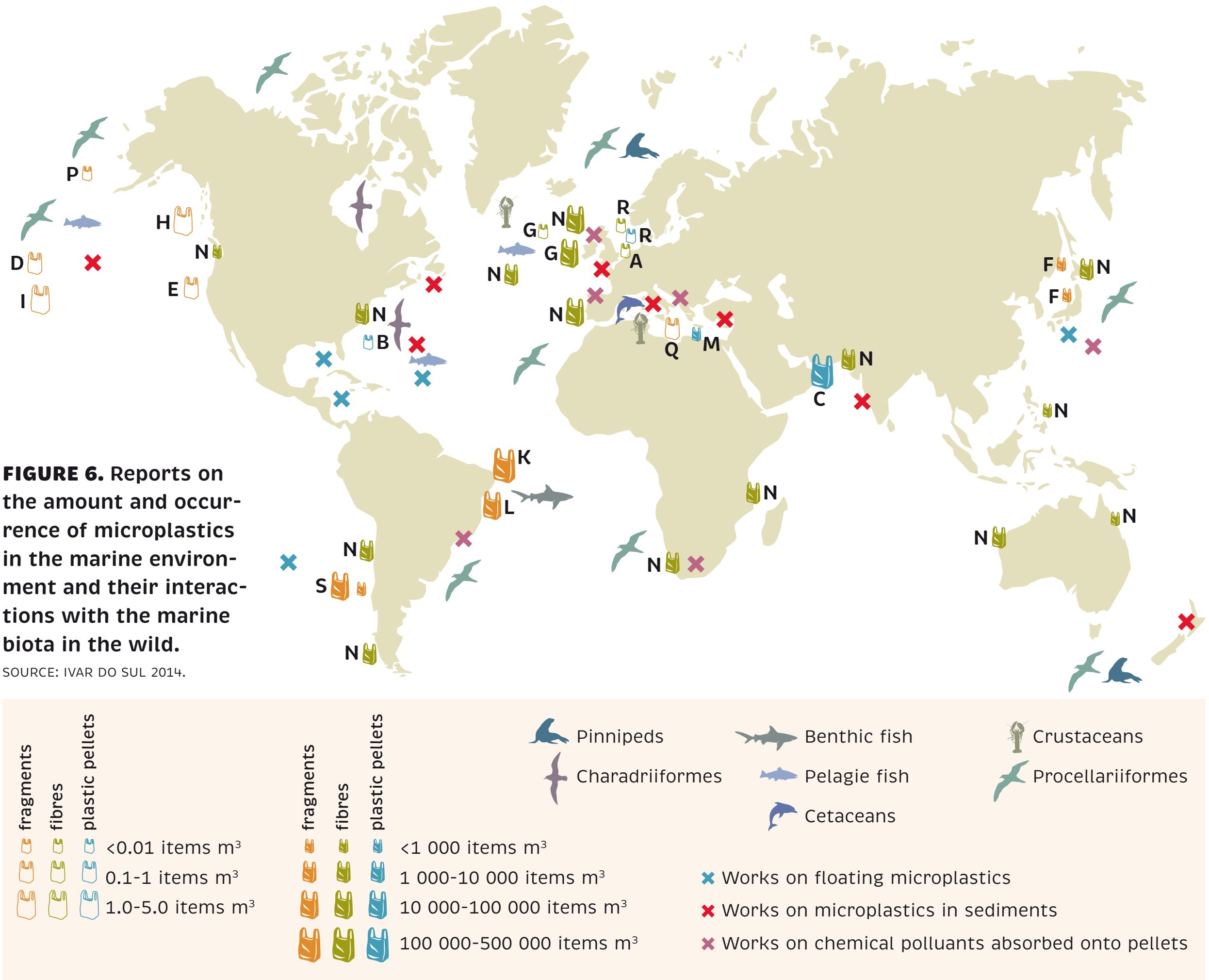


FIGURE 6. Reports on the amount and occurrence of microplastics in the marine environment and their interactions with the marine biota in the wild.

SOURCE: IVAR DO SUL 2014.

Plastic bags represent the average number of items per cubic meter of seawater (outline symbols) or sediment (filled symbols) observed and/or estimated. **A** Buchanan, 1971; **B** Carpenter et al., 1972; **C** Khordagui and Abu-Hilal, 1994; **D** Moore et al., 2001; **E** Moore et al., 2002; **F** Kusui and Noda, 2003; **G** Thompson et al., 2004; **H** Lattin et al., 2004; **I** McDermid and McMullen, 2004; **J** Ng and Obbard, 2006; **K** Ivar do Sul et al., 2009; **L** Costa et al., 2010; **M** Turner and Holmes, 2011; **N** Browne et al., 2011; **P** Doyle et al., 2011; **Q** Collignon et al., 2012; **R** Dubaish and Liebezeit, 2013; **S** Hidalgo-Ruz and Thiel, 2013. The crosses represent works that registered microplastics outside of the scale used here.

4.1.1. Ecological and physical harm

Primary impacts of marine litter are ingestion (which can cause internal blockage, abrasion and release of pollutants) and entanglement, with more than 660 marine species reported to be impacted (Ivar do sul et al 2014) (Figure 7). The larger plastic items such as netting pose risks of entanglement for many marine organisms, while smaller particles including virgin pre-production pellets may be ingested and induce physical and chemical stress. Except in the case of occlusions (sea turtles, and some marine mammals) or storage by some species (procellariforms), excretion of ingested indigestible particles with feces is very common for most species. Nevertheless, a number of harmful effects of ingested litter have been reported; the most serious effects of these are the blockage of the digestive tract and internal injuries by sharp objects, which may be a cause of mortality (Katsanevakis, 2008) in marine biota (Ivar do sul et al 2014).

Very small (nano-size) microplastics have been shown to cross cell membranes, under laboratory conditions, causing tissue damage. Ingested microplastics can affect the physiology of the host organism and potentially compromise its health. Interactions of marine fauna with plastics can also lead to chemical harm or toxic endpoints As plastics debris concentrate chemicals present in seawater. This results in exposure to persistent, bio-accumulating and toxic (PBT) substances concentrated by plastics from sea water, and leaching of plastic additives, such as phthalates (Wright *et al.*, 2013), which may lead to their bio-magnification in tissue and be transferred to other parts of food web.

However, there is still inadequate monitoring to fully document the occurrence of microplastics and studies on their transfer in the marine food chain (Figure 7). In particular, the potential impact of macro and especially microplastics on large filter feeding marine organisms such as baleen whales or sharks is only recently explored (Fossi et al 2012, Fossi et al 2014). Very little information are reported until now on the impact on Baltic sea marine fauna.

4.1.2 Concentration and release of pollutants by aquatic plastic

There is growing concern regarding the persistent, bioaccumulative and toxic chemicals (PBT) {such as polycyclic aromatic hydrocarbons (PAH) and pesticides} sorbed into plastics. Microplastics may serve as vectors for these highly toxic pollutants allowing them into the marine food web. The chemicals can accumulate in the fatty tissue of ingesting organisms (Rochman *et al.*, 2012), posing a long-term risk to the health of the marine ecosystem.

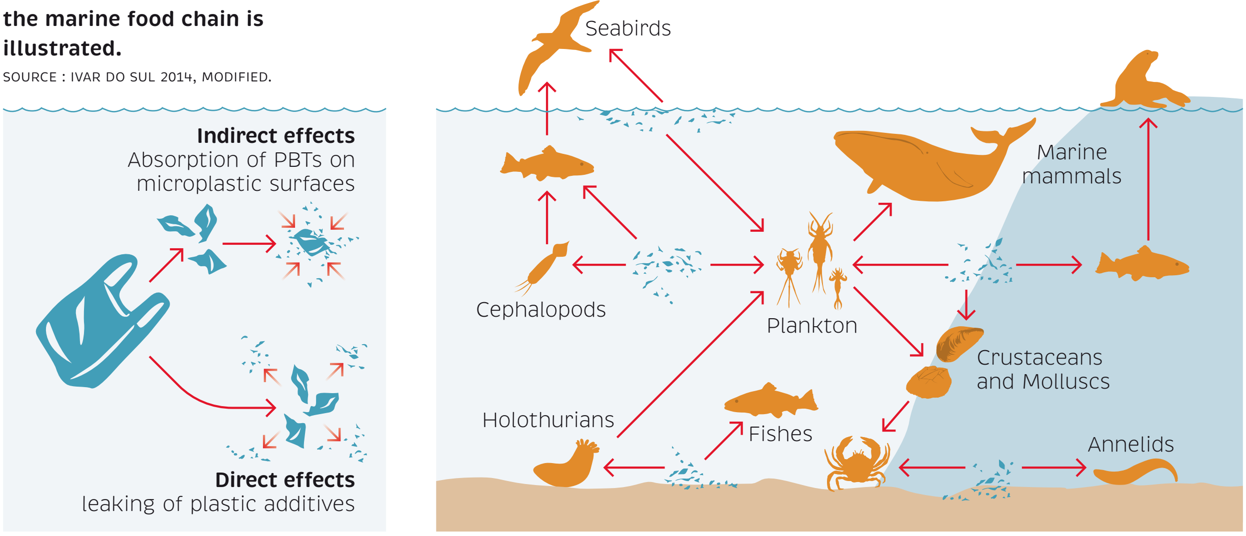
One major toxicological aspect of plastic litter in the marine environment and, consequentially, on marine organisms, is the enhanced the transport, accumulation, and bioavailability of PBT substances. Some of these are additives or chemicals added during compounding of plastics to enhance their performance (such as phthalates, nonylphenol, and brominated flame retardants). Others, such as bis-phenol A, are residual chemicals from the manufacture of plastics. In addition to the direct (or intentionally added chemicals) the plastics also carry chemicals acquired from environment.

The eco-toxicological effects of micro- and macro-plastics exposure in marine organisms and in the marine food web (see figure 7), need to be investigated in depth , with a particular focus on the following:

a. Chemicals acquired from environment. Plastic debris may be a sink for toxic chemicals from the environment that care sorbed into the debris and be released once inside the gut of the organism (Engler, 2012). Since PBT chemicals, generally, have low solubility in seawater they tend to migrate into water microlayers where they may be biomagnified. PCBs and DDE are sorbed by plastics debris efficiently with partition coefficients, Kd, of approximately 100,000-1,000,000 over seawater. For instance, phenanthrene, a PAH, partitions to plastic debris 13,000-fold over seawater (Engler, 2012). Moreover, the sorption of perfluorooctanesulfonate (PFOS) and perfluorooctanesulfonamide (FOSA) on microplastics is highly linear, and it indicated that partition by hydrophobic interactions to be the predominant sorption mechanism. Most of these chemicals if bioavailable, can potentially affect organisms adversely (Teuten *et al.*, 2007).

FIGURE. 7. **A conceptual model to the potential trophic routes of microplastics in the marine environment across vertebrate and invertebrate group. The transfer and ecotoxicological effects of direct (intentionally added) and indirect (acquired from environment) chemicals in plastics on the marine food chain is illustrated.**

SOURCE : IVAR DO SUL 2014, MODIFIED.



b. Chemicals intentionally added to plastics. Several additives are mixed in with plastics during compounding and processing of the material into products. Some of these are used in significant concentrations. For instance, phthalates a class of chemicals commonly used to make soften rigid PVC may be used in excess of 50 wt. percent in the plastic. Phthalates may leach from plastic debris on a fairly steady basis but generally do not persist in the environment. Di-(2-ethylhexyl) phthalate (DEHP) is the most abundant phthalate in the environment; DEHP, in both invertebrates and vertebrates, and is rapidly metabolized yielding its primary metabolite, MEHP (mono-(2-ethylhexyl) phthalate), that can be used as marker of organisms exposure to DEHP. It is known that additives bisphenol A (BPA) or nonylphenol (NP) may have biological effects already at very low concentrations in the ng/L or mg/L range, especially for molluscs, crustaceans and amphibians (Oehlmann et al., 2009).

4.1.3 Endocrine disruptors

With ingestion of micro- or mesoplastic particles, the amount of leached additive bio-available to the organism is small. However, among the additives are known endocrine disruptor chemicals (EDCs) that are effective at very low concentrations. EDCs are chemicals where the molecular features are similar to those of hormones secreted by the endocrine system. In the body they interfere with the physiology controlled by the endocrine organs (hence called EDCs). Similar to hormones they act at very low concentrations, have non-linear dose-response curves and may display inter-generational effects in animal studies. Typically the reproductive functions and growth patterns of the organism are perturbed by EDCs. This very low concentrations of these in animal tissue is a concern; the potential of EDCs being transferred via the marine food web and reaching the human consumer is even more of a concern.

Of the chemicals used in plastics industry phthalates, brominated flame retardants and nonyl ethoxylates are well documented as having ED activity. In the case of polycarbonate plastic, the residual monomer bis-phenol A is also a potent EDC.

4.1.4 Aquatic plastic as an important vector for the transport of alien species and microbes

An “Invasive alien species” is commonly defined as a one whose introduction or spread in an ecosystem has been found, through risk assessment, to threaten its biodiversity and ecosystem services. Alien species may also have a negative impact on human health or the economy. Numerous studies have suggest that the availability of floating litter can greatly assist the transport of such species beyond their natural boundaries and introduce them into environments where they were previously absent (Barnes and Milner, 2005). Barnes (2002) estimated that human litter more than doubles the rafting opportunities for biota, assisting the dispersal of alien species. Usually, the first animals colonizing plastic surfaces are suspension feeders (foraminifera, polychaetes, bryozoans, hydroids and barnacles). The plastic in seawater may be entirely covered by rafting organisms in just a few months of exposure (CIESM, 2014). However, very few studies on the role of marine litter in the introduction and spread of alien species exist in European Seas and in Baltic sea in particular. Rafting species or the plastisphere members may be opportunistic pathogens such as specific members of the genus *Vibrio* that dominated in some oceanic plastic samples (Zettler et al 2013). Plastisphere communities are distinct from those in surrounding surface water, implying that plastic serves as a novel ecological habitat in the open ocean.

There is an urgent need to study the phenomenon in Sweden to ensure the protection of local aquatic biodiversity.

4.2 Microplastic and human consumer impacts

As describe above, microplastics are present throughout the marine environment and ingestion of these plastic particles by a wide array of marine organisms has been demonstrated in laboratory studies. Van Cauvenberge et al (2015) investigated the presence of microplastics in two species of commercially grown bivalves: *Mytilus edulis* and *Crassostrea gigas*. Microplastics were detected from the soft tissues of both species. At the stage of human consumption, *M. edulis* contains on average 0.36 ± 0.07 particles g-1 (wet weight), while a plastic load of 0.47 ± 0.16 particles g^{-1} (wet weight) was detected in *C. gigas*. As a result, the annual dietary exposure for European shellfish consumers can amount to 11,000 microplastics per year. These estimates raise concerns on the possible contamination of marine seafood by microplastics and the potential threat posed by the microplastics to human food safety. But given the lack of sufficient data, estimating the potential risks for human health posed by microplastics in foodstuffs is not yet possible.

Challenge 2.1: Evaluate the potential pathways of microplastics transfer in the aquatic food chain. *As marine plastic affects different ecological compartments, the study of its impact on marine food chain at all trophic levels is of increasing importance.*

At present, there are only a few studies on the bioaccumulation of plastics and their associated PBTs across marine trophic levels. With regard to biodiversity, it is essential to focus research on ingestion by invertebrates, fish, turtles, seabirds and marine mammals. There is also evidence on ingestion by epipelagic and mesopelagic fish, with the possibility of bioaccumulation and transfer through the food web. There are currently no conclusive reports on the transfer of microplastics to higher trophic levels and whether they act as a vector for bioavailable contaminants. Studies are needed to understand the capacity for microplastics and their associated contaminants to be transported along marine food webs via trophic interactions as well as an estimation of population and ecosystem level impacts (Wright et al. 2013). Moreover, the potential transfer to the human consumer it is an essential topic to investigate.

Sentinel organisms need to be selected for the monitoring of content (including detection of plastic additives concentrations and Persistent Organic Pollutants (POPs)) and effects (biomarker responses) of marine plastic in different ecological compartments (water column, sea bottom, coastal shore) and with different sized biotopes (wide-, medium and spot)(CIESM, 2014). Selected sentinel species can be proposed as bioindicators for marine litter (macro- and microplastic) and for the implementation of the EU Marine Strategy Framework Directive (Descriptor 10).

Challenge 2.2: Quantifying the chemical exposure risk from ingested microplastics. *Evaluate the potential pathways and rates of chemical transfer and ecotoxicological risk, for target species.*

The main ocean and freshwater ecological impact related to microplastics is via the leaching of PBT contaminants from ingested microplastics in marine organisms and need to be better defined and understood. There is some evidence of distress from mechanical or physical effects due to ingestion. The potential effects of EDCs via the leaching of contaminants and plastic additives from ingested microplastics in aquatic organisms need to be better understood. There is a need to develop (also using *in vitro* approach in laboratory studies) the specificity of biomarkers to microplastic exposure (plastic additives and PBT substances). This would help track a cause and effect relationship.

Challenge 2.3: Evaluate the potential significance of plastics and microplastics as a vector for organisms and microbes. *The extent to which floating plastic litter may contribute to the introduction of exotic species and pathogens has to be questioned.*

As nature's biodegraders and recyclers, microorganisms may play a role in mitigating the impact of plastic in the marine environment, or alternatively, plastic may serve as a vector for transport of pathogenic microorganisms into marine fauna. Improving our knowledge of the ecology of microbial life on the "plastisphere" is of great importance to better understand (i) the potential risk of pathogen dispersion by plastic debris transport around the oceans (ii) the fate of toxic molecules sorbed in plastics that can be degraded by microorganisms, and (iii) the potential for microbial degradation of synthetic plastic itself.

Challenge 2.4: Promote investigation to evaluate degradable plastics impacts. *We need a better understanding of degradation of "biodegradable" materials with enhanced degradation properties, as there is concern they may break down into fragments of limited degradability.*

The development of biofilms on plastic surfaces both on conventional plastic and "biodegradable" materials in the marine environment has not been extensively studied in relation to their interaction with pollutants, and properties such as behavior, sorption/desorption and ability to degrade organic pollutants must be better understood.

Challenge 2.5: Evaluate the potential significance of human consumer impacts. It is also important to identify potentially vulnerable/target species at different trophic levels and to rank POPs and additives according to their potential for enhanced bioaccumulation in these species via ingestion of plastics. The question as to what extent the ingestion of microplastics by marine organisms constitutes a potential risk to the human seafood consumer is not yet fully understood at this time and requires further research.

5 Focus Area 3: Consuming plastics

The sustainability challenges posed by plastics consumption relate to two principal issues: to reduce absolute volumes of consumption of the material, and/or reduce the environmental implications of those plastics that are consumed. Over-riding both challenges is the question of whether plastics represent more or less sustainable options than do other materials, especially when accounting for multiple issues such as CO2 emissions, pollution and toxicity. Only through the relationship between producers and consumers can sustainable plastics use be achieved – each has a part to play. With respect to consumers, five core areas need to be considered: systematic measurement of the environmental implications of different plastic containing consumer products; reducing the volume of plastics consumed; increasing recycling rates of plastics; better understanding the cultural significance of plastic and how it is valued; and, identifying how everyday practices are changing in order to recognize likely future plastics demand.

5.1 Measuring the sustainability of plastics consumption

Plastics have some virtues with respect to its environmental impacts when compared with other materials, such as metal, glass and wood. The first critical set of understandings required to maximize resource efficiencies is, therefore, to identify the environmental hotspots in plastics production and consumption and where sustainability gains can be made by material substitution and material or product innovation. For instance, the recent innovation with PET soda bottles where a part of the conventional plastic is substituted with a partially bio-based equivalent, directly contributes to efficient use of fossil-fuel resources. The bio-based PET has identical functionality to the conventional resin it replaces. Life-cycle assessment (LCA) techniques that explore the processes and material inputs that produce goods and account for how those goods are used through their consumption are necessary for identifying environmental impacts and informing policies (Baumann, et al., 2004).

In addition to accounting for the environmental implications of the production and consumption of plastics it is important that such analytical techniques take account of system (e.g. within and across product sectors) level processes in order to fully account for potential rebound effects where resource-efficiency gains in one part of the system (e.g. reduction of plastics in food packaging) have adverse affects in other parts (e.g. faster rates of food degradation leading to greater food waste – see Plumb et al. (2013) for a discussion of food packaging and waste). Complete and accurate measurement of the environmental implications of plastic use across and within systems is necessary to identify 'hot spots' of resource intensity and inform public policy, industrial strategy and consumer understandings of the environmentally optimal configurations of plastic use.

5.2 Reducing absolute volumes of plastic consumption

Reducing the absolute volume of plastic consumed and avoidance of substitution of plastics with less environmentally problematic materials will require changes in consumer behavior. This can take the form of reducing the consumption of particular goods or the re-use and prolonged life of existing goods. Perhaps the best examples of attempts to reduce the consumption of a plastic good can be found in schemes aimed at consumers using fewer plastic bags when shopping. Relatively standard 'behavior change' initiatives have been employed, such as limiting accessibility to the good (e.g. customers have to ask for a plastic bag at the checkout), imposing a small charge for the purchase of the bag, or removal of the option to the customer altogether (Munasinghe et al., 2009). Similarly, information campaigns to reduce plastic product packaging (especially in relation to products like toys and special occasion gift products like Easter eggs) have met with some success in reducing plastics use.

Other approaches have focused on product substitution, such as the marketing of re-fillable (multiple use) plastic bottles as an alternative to single-use PET bottled water. In these examples the products concerned are explicitly plastic goods. However, much plastic use is embedded in other products, such as electronic durables, sporting equipment, and domestic furnishings. Consequently, reducing the volume of total plastics consumed also requires a consideration of how a wide range of products can minimize their plastics components while maintaining acceptable levels of performance and quality to the consumer or the lifetime of such products can be extended. This is partly a matter of product design, and partly a matter of consumer preferences and perceptions of the 'value' of plastics products (see also section 5.4).

5.3 Increasing rates of plastics recycling.

There is a limit to absolute reductions in the volumes of plastics consumed, not least because in some instances plastics are more sustainable than alternative materials. In such contexts, the recovery of plastics for recycling is important, and represents another area where consumers have a critical role to play. A not inconsiderable secondary benefit of effective recycling, in which consumers are motivated to dispose of plastic waste responsibly, is that it can reduce plastic littering and help avert pollution of eco-systems, such as marine and freshwater environments (see section 4).

Collection of plastic wastes can be done by 'bring-schemes' or through curbside collection. The latter, which require the least effort or inconvenience to the consumer tend to have higher success rates, although largely in relation to plastics consumed in the home. This is problematic as much plastic consumption takes place outside of the home (while travelling, in the workplace, schools, and so on). It is also important to take account of variations across different social groups in their capacity to act. Collection of used plastics from households is more economical and effective in locations of high housing density (e.g. the suburbs or in large multi-apartment buildings). Identification of schemes and organizational innovation to facilitate more flexible and multi-site disposal of plastic waste (see also section 6) is therefore important (Hopewell, et al., 2009).

Most recycling schemes are premised on voluntary consumer actions, emphasizing the need to inform, encourage and enable consumers to dispose of their waste appropriately. The focus of attention, therefore, centers on motivating consumers to act. As the 'value – action' gap suggests, simply informing, encouraging and enabling is not particularly effective at changing human actions. Surveys continue to reveal that most consumers (in most affluent countries the figures consistently show around 80% of those surveyed) have pro-environmental attitudes (stated preferences), including strong convictions of the importance of recycling and reduction of packaging. Yet, surveys that examine reported behavior (revealed preferences) consistently show that pro-environmental actions remain limited (Defra, 2008; Vermier & Verbeke, 2006). As argued elsewhere (Warde & Southerton, 2012), the value – action reveals a critical lacuna in academic and policy understandings of consumption that too easily assume individual deliberations and consistency of values when devising policies. Rather, research suggests that habitual and routine behaviors (see also section 5.5) represent the critical forms of human action that need to be understood if behaviors like increased rates of recycling are to become 'normal' and taken-for-granted (habituated) actions in everyday life.

5.4 Shifting consumer perceptions and the cultural 'values' of plastic

Whether because of its relatively short history or its ubiquity the cultural valuing of plastics is under-researched. Little is know about how consumers understand and value plastics. The cultural valuing of plastic as a material, or material component of the goods that we consume, is somewhat hidden. Compared with other materials such as wood and metals the cultural meanings of its consumption can only be interpreted based on generic trends related to cultural consumption. That much consumption of plastic relates to single-use disposable products might suggest, for example, that the material has cultural associations with cheapness and is a material that contributes to a throwaway culture (Cooper, 2010). Such cultural associations are not fixed – they change over time and vary across cultural groups. What constitutes waste, or more precisely what renders a good as being deemed 'used-up', 'obsolete' or ready for disposal, is an example of how the cultural associations of goods change with direct implications for patterns of consumption (see Evans (2014) for a discussion of the changing cultural meanings of food waste). Insights into cultural perceptions of plastic as a material of consumption therefore offers opportunities to consider how the design and communication (e.g. through marketing) of plastic products could shift consumer perceptions in directions that reduce volumes of its consumption (e.g. reduce single-use) or that foster a cultural valuing of the product that encourages consumers to recycle.

Understanding the cultural valuing of materials such as plastic will also require consideration of broader socio-cultural processes of change. An example of shifting cultural values can be found in contemporary preferences for 'authenticity', often captured by consumer preferences for craft consumption that celebrates the use of traditional materials such as wood, retro or distressed styling of goods, and antiques (Campbell, 2005). The individualized characteristics of such goods allows for forms of personalization that offer the capacity for symbolically communicating identity and lifestyle (Bauman, 2007). And, such cultural properties are not only sources of symbolic value but also economic value – despite lower utility value, goods associated with 'authenticity' often carry a price premium.

Plastic has material properties that are highly malleable for the purposes of design and packaging. In her research on bottled water, Hawkins (2013) demonstrated how the design of disposable plastic bottles conveyed a range of cultural meanings and associations that facilitated brand and product differentiation – whether associated to 'sport and fitness', 'health', 'taste', or 'well-being'. This was not simply a matter of marketing. Bottles were molded into designs that expressed the brand association, such as narrow grip designs for sport-oriented bottles. Further research into the symbolic (communicative), cultural (meanings) and economic valuing of plastic goods is necessary if consumer perceptions of this material are to be fully understood. Such valuing is likely to vary across social groups (related to variables such as age, generation and life course, ethnicity, and social status) and product categories, and understanding such variations is critical for unpacking the very broad sector-specific (e.g. as shown in Table 1) understandings of consumer demand.

5.5 Understanding the dynamics of everyday practices and the changing demand for plastics

The ways in which plastics are appropriated into everyday practices shape its consumption. Plastic has facilitated the emergence of an array of practices that are now taken for granted – especially practices related to the use of consumer electronics. Clarke's (2001) social history of 'Tupperware' provides a fascinating insight into the processes through which this form of plastic was appropriated into American culture and social life. Tupperware had clear utility value – light, durable, and available in multiple shapes and sizes – and a cheap method of storage. But, of greater significance to its popularity was the development of a range of associated practices such as the 'Tupperware party': this plastic became a source of sociability and in doing so its users learned from each other both how to use it and imparted cultural values into the product. Clarke's is an account of how plastic was appropriated, has shaped, and subsequently become a normal feature of ordinary everyday lives.

As Clark's study suggests, plastic plays a role in developing cultural conventions (i.e. taken-for-granted ways of doing everyday life). In domestic cleaning products and utensils, plastic has played a crucial role in emergent cultural conventions related to cleanliness (Shove, 2003). Anti-bacterial and disposable plastics (to be discarded immediately after 'contamination') have re-shaped what it means and how to competently perform everyday domestic practices, such as household cleaning and food preparation. In these ways plastic as a material interacts with the changing cultural conventions and skills required to perform any practice competently to shape a huge range of everyday, ordinary and normal social practices (see Shove et al. for a discussion of social practices and dynamics of change). The performance of such practices take the form of habitual (practices performed in 'auto-pilot' following tacit rules and procedures) and routine (sequential and periodic) forms of human action that are not particularly conducent to change through appeals to consumers on the basis of individual choices or deliberations (Southerton, 2013).

The critical questions raised are threefold. In what ways do the material (e.g. plastic) interact with cultural conventions and the skills required to perform any given practice competently? Second, how are plastics appropriated into practices and how does that appropriation change the practice in ways that render plastic consumption normal (and often essential) in everyday lives? Addressing this question is essential if habitual and routine consumer behaviors are to be understood and reconfigured. Finally, how can processes of plastics appropriation and practice change be identified in order to better understand future demands (or future practices) for plastic consumption? These are big questions that seek to explore the relationships and interactions between the material, its use and its cultural meanings in shaping consumer demand. Addressing these questions will provide additional insights into the dynamics of consumer practices and the opportunities for shaping or steering plastic consumption in directions that reduce its environmental impacts.

Challenge 3.1: Develop systematic measurements of the environmental costs of plastic consumption.
Research that examines, measures and identifies environmental 'hot spots' of plastics consumption is urgently required. This research needs to fully account for sys-

tems level processes that include the production and consumption of plastic products, and potential rebound effects within and across sectors. Sweden has existing expertise in techniques such as life-cycle assessment that needs to be harnessed in order to develop the evidence-base required to inform and guide public policy, industrial strategy and consumer understandings of plastics use and sustainability.

Challenge 3.2: Identification and promotion of plastics consumption reduction.
Reductions of absolute volumes of plastic consumption are a major challenge given the utility of the material. Sustainability gains can be achieved by minimizing plastics use through changing consumer behaviors and promoting the re-use of plastic products, especially by harnessing longer consumer product lifetimes. There is a need to develop understandings of how consumers can reduce their plastics consumption and reuse the plastics that they do consume.

Challenge 3.3: Making recycling the habitual and routine mode of plastics disposal.
Plastics will continue to be an ever-present material in everyday lives, and in some cases may represent the more sustainable option in product design. Recovering plastics and creating demand for recycled products will therefore continue to represent a significant challenge. Recycling of plastics products will need to become habitual and routinized, and research is necessary to understand the most effective mechanisms for such habituation across social groups that vary with respect to their socio-demographic, socio-economic and geographical characteristics.

Challenge 3.4: Understanding consumer perceptions of plastic and enhancing its cultural valuing.
Research into the cultural valuing of plastics is scant. The consumption of plastics often involves either cheap single-use products or the material is embedded in other products. How consumers perceive plastic and the cultural associations and meanings of the material requires better understanding if its design potentials are to be utilized for encouraging more sustainable use.

Challenge 3.5: Revealing plastics demand by exploring changing patterns and trajectories of everyday consumer practices.
Plastic underpins a bewildering range of 'taken-for-granted' and 'normal' everyday practices. Understanding the role that plastics plays in how everyday practices change is essential if we are to have a better understanding of future plastics demand. Identifying how consumer practices are developing (or, in some cases, disappearing) and anticipating future patterns of demand is critical for achieving greater sustainability outcomes of plastics use.

6 Focus Area 4: Improving Plastics Waste Management

Sweden already enjoys a strong recycling culture. This ethic of collective social responsibility, along with the current infrastructure for collecting recyclable waste streams gives the country a strong foundation for the future. But more recycling of plastic waste that will otherwise incinerated (in waste-to-energy plants) is environmentally desirable. Also to be able to meet the European Union goals to reuse or recycle 50% of all household plastic waste (along with paper, metal, and glass), Sweden will need to add to its efforts.

Between 2012 and 2013, the amount of treated municipal waste in Sweden increased by 1.1%. Just a little over 50% (50.3%) of it was sent to energy recovery in 2013, while 33% of waste went to material recycling, an increase of 3.3%. According to Avfall Sverige (Swedish Waste Management) the recycling figure can be increased. The largest determinant for the amount of household waste that is recycled as well as the degree of sorting in the system chosen for collection. Increasing the quality and quantity of recycled plastics will require more residential sorting and widespread curbside collection, Avfall Sverige contends.

We believe collection would rise dramatically should the responsibility for collection fall on the municipalities rather than the producers. That would see a rise in availability of recycling stations and curbside collection. Availability is the key. In this form, municipalities would be responsible for designing the collection, and the producers would reimburse the municipalities and recycle the material.

> ***It is very clear that it is difficult to increase recycling rates in the current system, regardless of communication programs. The systems with curbside collection of packaging material today, like Lund or Helsingborg, indeed have by far the highest ratio for recycling and in the "purest" material flows.***
>
> **Jon Djerf, Avfall Sverige**

In Europe, packaging applications are the largest application sector for the plastics industry and represent 39.4% of total plastics demand. Moreover, packaging dominates the waste generated from plastics, and is responsible for 62.2% of all plastic waste. In 2012, 26.3% of all European plastic waste was recycled, Norway led the region with 36.9%. Sweden also rates high at roughly 34%.

Still, it is not surprising that one area of specific concern for plastics recycling in Sweden is the low level of recycling of plastic packaging waste from households. One survey shows that 30% of a household garbage bag is packaging and newspapers. In 2013, 74.7 kg of total packaging was recycled per capita. Of that figure, only 5.6 kg, or 7.5%, was plastic. Paper and glass were collected in far higher quantities by weight.

Efforts to increase the quantity of plastics recovered from the waste stream for recycling can also benefit other waste reduction efforts. For example, Avfall Sverige says it would welcome more research in the social behavioral field comparing different collection systems for diverse material streams. Topics would include insights into thresholds and triggers for action, as well as information and feedback flows.

Innovations in the design and content of the packaging itself through product development could help reduce the amount of packaging material needed, and enable easier and higher quality recycling. Better-designed packaging could also minimize food wastes.

Challenge 4.1: Understanding consumer attitudes that limit the recycling of household packaging waste.
What are the factors that explain why packaging plastics, in particular, end up in household trash? What unstated habits or rules of thumb do Swedish households follow that prevents them from including packaging plastics in their recycling?

Challenge 4.2: Studies on limitations in available infrastructure and stakeholder responsibility on recycling rates of household plastic waste.
Identify and closely characterize key waste streams that can be recycled but are not (i.e. plastics packaging in consumer waste or mixed construction debris). Obtain or research cost-benefit measurements for different waste recycling schemes for urban, semi-urban, and rural communities including curbside, neighborhood-based, or other collection schemes as well as consumer sorting versus single stream recycling. Is responsibility and cost-allocation for waste diversion efforts distributed fairly across stakeholder groups such as manufacturers, retailers, consumers, and waste handling organizations? Is demand (price) for recycled material too low to cover the cost of collecting and processing it?

Challenge 4.3: Identify and develop best practices in technology appropriate to Sweden to ensure increased recycling of plastic waste.
Identify benchmark technologies and best-in-class processes for increasing recycling rates beyond 34% to help build a roadmap to reach the EU's goal of 50% household recycling rates by 2020.

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