# SUSTAINABLE PLASTICS

## ENVIRONMENTAL ASSESSMENTS OF BIOBASED, BIODEGRADABLE, AND RECYCLED PLASTICS

JOSEPH P. GREENE

SECOND EDITION

WILEY

**Sustainable Plastics**

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## Environmental Assessments of Biobased, Biodegradable, and Recycled Plastics

Second Edition

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# 1

# Introduction to Sustainability

## 1.1 Sustainability Definition

Sustainability has many definitions. The most common definition of sustainability has its roots in a 1987 United Nations conference, where sustainability was defined as "meeting the needs of the current generation without compromising the ability of future generations to meet their needs" (WCED 1987). Sustainable materials, processes, and systems must meet this definition and not compromise the ability of future generations to provide for their needs while providing for the needs of the current generation. Thus, for plastics manufacturing, materials and processes used today should not deplete resources for future generations to produce plastic materials.

Sustainability can be measured by the outcomes of using a material, process, or system on the environment, society, and economy. The three components of sustainability have economic, social, and environmental aspects and are related with each other as shown in Figure 1.1.

Materials, processes, and systems can have environmental, economic, and societal impact. Sustainable materials, processes, and systems have all three impacts. For example, the development of materials will have environmental impacts of using raw materials, energy sources, and transportation that come from natural resources, which can create air, land, and/or water pollution; economic impacts are creating commerce, jobs, and industries; and societal impacts are creating roles for jobs and services. Some new materials for clothing were evaluated for sustainability (Provin et al. 2020). They found that relating new materials to the sustainable development goals of 2030 Agenda from the United Nations is necessary due to the important issues presenting challenges at the global level, in relation to the economic, social, and environmental pillars of sustainability.

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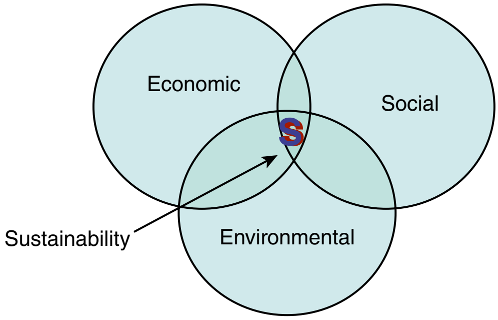


**Figure 1.1** Sustainability definition.

Organizations are often analyzed with a "Triple Bottom Line" approach to evaluate the social, economic, and environmental performances of a company (Vanclay, F., 2004). This approach is the key to creating a sustainable organization. The "Triple Bottom Line" was used for biofuels as an excellent example of a sustainable fuel (Sala 2020). Biofuels meet the new economic paradigms that are related to the green economy, the bio-economy, and the circular economy. They developed an essential approach to apply life cycle thinking to production and consumption patterns to evaluate environmental and socioeconomic burdens and benefits, in an integrated manner. Lastly, they found that for socioeconomic sustainability, the assessment is going beyond the profit- and finance-oriented perspectives, including instead externalities associated to the activities under evaluation.

Examples of sustainability measures were developed for using a holistic approach from sustainability measurements of technology use in the marine environment (Basurko and Mesbahi 2012). The environmental effects of ballast water were measured with an integrated quantitative approach of sustainable assessment. The systematic approach can provide environmental, economic, and social sustainability for marine technologies.

The sustainable tool allows for the inclusion of sustainability principles to the design and operations of marine products. Sustainability can be effectively incorporated into the design phase of products and services and create reduced environmental, social, and economic impacts. The sustainable tool was created with LabView® software with SimPro® life cycle assessment (LCA) program to provide an integrated approach with a single indicator to reduce the environmental, social, and economic impacts of ballast water effects on the ocean quality. Another approach for the triple bottom line in sustainability was found for biomass ethanol production in China (Wang et al. 2020). They used a multi-regional input output (MRIO)-based hybrid LCA to estimate the sustainability of ethanol production in China. Employment, economic stimulus, and energy use were assessed. Bioethanol was found to be more effective on energy savings and economic stimulus than regular gasoline. Second-generation bioethanol had the highest energy return on the investment. Lastly, supply chain sectors make up the majority of social and environmental impacts.

### 1.1.1 Societal Impacts of Sustainability

The first aspect of sustainability can measure the impacts of products and processes on the society. The societal impact of using a material and manufacturing process can be measured by the effects on the population and the roles of the workers in the community. Sustainable manufacturing processes are defined as providing proper wages for the workers and a clean and safe work environment. The method and environment of producing a manufactured product can result in impacts on a person, group, and community. In another research work, sustainability was evaluated with supply chain management concepts (Vermeulen and Seuring, 2009). The authors propose three-generation approaches. Single firm approaches are the first generation. Joint product sector approaches are the second generation. And cross-sectoral approaches are the third generation. They propose that the various forms of sustainable supply chain governance clarify two aspects that have hardly been addressed in the general analysis of value chains: first, these varying forms of interaction, cooperation, and compelling rules in the value chain are an instrument of competition, partly based on specific quality assets of the products (namely the environmental and socio-ethical performance of value chain partners), and second, these forms of interaction and cooperation include other types of societal actor – apart from newly created nonprofit governance institutions and their (for profit) auditing and control bodies, consumer NGOs, development NGOs, and environmental NGOs also play diverse roles. They recommend that sustainable supply chain management and governance are important to companies, consumers, NGOs, and even governmental agencies. They propose that the challenges of climate change, energy provision, and creating wealth for an increasing world population will broaden the need for sustainability management and sustainable supply chain management and governance in the near future.

The wages, benefits, hours per week, safety, and other human resources provided to an individual worker contribute to the quality of the product or process and the ability of that product or process to maintain its presence in the marketplace. A workplace that produces a product or process without wages and benefits that are appropriate to the workers in the region can lead to high turnover rates of workers, poor worker morale, and loss of personal buy-in for workers. The product or service will not be sustainable since it may not last if few workers are available or the environment may suffer tragic losses due to health or safety concerns. Poor working conditions and poor wage structures may benefit the economics of the current company but may lead to poor working environments for future workers and thus is not sustainable.

Sustainable workplaces feature the maintaining of welfare levels in the future (WCED 1987). Welfare can be defined as a subjective measure of the sum of all individuals' utilities generated from the consumption of goods, products, and services (Perman et al. 2003).

### 1.1.2 Economic Impacts of Sustainability

The second aspect of sustainability can measure the economic impacts of using a material and manufacturing process to produce products. Sustainable manufacturing processes are defined as providing proper wages for the workers and clean and safe work environments. Economic impacts of sustainability can be measured with a capital approach that can be defined as maintaining economic, environmental, human, and social capital over time for future generations (Kulig et al. 2010). The capital approach can be proposed as a theoretical basis for sustainable development indicators (Atkinson and Hamilton 2003; World Bank 2006; UNECE 2014). The capital approach provides a theoretical approach by measuring all capital stocks in their own units. The capital approach can provide consistent, theoretically sound, and policy-relevant comparisons between countries (Kulig et al. 2010).

The economic benefits of sustainability were developed for water reuse. Sgroi et al. (2018) found that economics are the major barriers to actual development of water reuse. A holistic approach is needed to evaluate the sustainability of water reuse. Circular economy may lead to a "paradigm shift" to enhance resource recovery. Segregation at source may be a starting point for sustainable on-site resource recovery. The economic impact of using a material can be measured by the effects on the creation of jobs and industry for communities. The creation of jobs can lead to creation of taxable bases and tangible property. In addition, the use of sustainable materials and processes can lead to reduced energy, transportation, waste disposal, and utility costs for manufacturing operations. Sustainable enterprises can be defined as "Lean and Green," where manufacturing costs are minimized, and manufactured materials are made with reduced environmental impacts.

Recycling of metals, plastics, glass, paper, wood, waste inks and concentrates, waste oils, and industrial fluids can reduce the amount of trash that is sent to landfills and hazardous disposal sites and reduce the waste disposal costs. Use of recycled or bio-based plastics can reduce the manufacturing costs of some plastics. Use of lower energy pumps, motors, and lighting can reduce energy costs for plastics manufacturing.

The incorporation of sustainability into the business plan can lead to a design for sustainability paradigm where an eco-design approach can lead to integrating social, economic, environmental, and institutional aspects into the supply chain of an eco-friendly product line. This can lead to healthy organizations providing good jobs to healthy employees and contributing to the social network of the organization and community.

### 1.1.3 Environmental Impacts of Sustainability

The third aspect of sustainability can measure the environmental impacts of producing a product or system in terms of usage of natural resources for raw materials, energy, and real estate land. The production of plastic products can generate greenhouse gases (GHGs), solid and liquid waste, air pollution, water pollution, and toxic chemicals. Environmental aspects are measured with the life cycle process are explained later.

Strategic environmental assessment can be used to provide a basis for establishing sustainability for products and services (White and Noble 2013). Strategic environmental assessment can help ensure that policies, plans, and programs are developed in a more environmentally sensitive way. Strategic environmental assessment can support sustainability by providing a framework for decision-making, setting sustainability objectives, ensuring consideration of other sustainable of using strategic environmental assessment of sustainability. This can include some of the following:

- Providing a decision support framework for sustainability.
- Being adaptive to the decision-making process.
- Incorporating sustainability objectives and principles.
- Considering relevant sustainability issues early on.
- Adopting sustainability criteria.
- Identifying and evaluating other sustainable alternatives.
- Trickling-down sustainability.
- Capturing large-scale and cumulative effects.
- Enabling institutional change and transformational learning.

Environmental aspects of sustainability can be measured by monitoring resource depletion and pollution generation during the production of products or services. Resource depletion can include land use, energy usage, water usage, fossil fuel usage, among others. The pollution emissions can include GHGs, water pollution, air pollution, climate change, toxic chemical released, human toxicity, carcinogens released, summer smog creation, acidification, eutrophication, among others.

An important environmental concern is the increased amount of GHGs in the atmosphere. GHGs are gases in the atmosphere that absorb and emit thermal radiation within the thermal infrared range causing the planet to increase in temperature. During plastic manufacturing, GHGs are produced by the energy sources needed to mine the raw materials, processing the raw materials into pellets, conversion of the pellet into finished products, and transportation. GHGs comprise of gases that contribute to global warming by creating a layer of insulating gases that insulate the planet. These gases absorb and emit radiation within the thermal infrared range. GHGs include methane, carbon dioxide, water vapor, fluorocarbons, nitrous oxide, and ozone.

Carbon dioxide is the largest contributor to global warming due to its volume. Methane has a global warming rate of 22 times the rate for carbon dioxide. Typically, the production of these gases is listed in LCAs as CO2 equivalent (CO2eq). Thus, the formation of GHGs is listed as CO2eq. Reductions in GHGs can be done with lowering energy usage for products and services.

## 1.2 Green Chemistry Definitions

The American Chemistry Institute established green chemistry principles. The green chemistry engineering principles provide a framework for scientists and engineers to design and build products, processes, materials, and systems with lower environmental impacts. Green chemistry principles can be used to develop chemical products and processes that reduce or eliminate the use and generation of hazardous or toxic chemicals. The 12 principles of green chemistry are as follows (Anastas and Warner 1998):

1) Prevention
2) Atom economy
3) Less hazardous chemical synthesis
4) Designing safer chemicals
5) Safer solvents and auxiliaries
6) Design for energy efficiency
7) Uses of renewable feedstock
8) Reduce derivatives
9) Use of catalytic reagents
10) Design for degradation
11) Real-time analysis for pollution prevention
12) Inherent safer chemistry

Prevention of waste generation during the manufacturing of the chemicals can help reduce environmental impacts of chemical production. Atom economy guides developers in incorporating all materials in the creation of chemicals. Synthetic chemicals should be created with little or no toxicity to the human health and the environment. Solvents, separation agents, and other auxiliary substances should be used sparingly or not at all. Energy usage should be minimized in the creation of chemical substances. Renewable feedstock should be the material source of the chemical substances rather than fossil fuel-based sources.

Creation of unnecessary intermediates or derivatives should be minimized or avoided if possible to reduce chemical waste. Catalytic reagents should be used rather than stoichiometric reagents. Chemical products should be designed to biodegrade in a disposal environment rather than be a persistent pollutant. Real-time, in-process monitoring and control of hazardous substances should use analytical methodologies. Chemical substances and processes should minimize the potentials for accidental chemical spills, explosions, and fires.

The 12 green chemistry definitions can be grouped into three areas: reduction in energy usage, reduction in waste, and reduction in pollution. The reduction in energy area includes design for energy efficiency, use of renewable feedstock, and reducing derivatives principles. The reduction in waste area includes prevention, atom recovery, and use of catalytic reagents principles. The reduction in pollution includes less hazardous chemical synthesis, reducing derivatives, designing safer chemicals, designing safer solvents and auxiliaries, design for degradation, pollution prevention, and inherent safer chemistry principles. These three areas are used to define sustainable manufacturing.

Recently, a chapter in a book on green chemistry studied the importance of sustainability to business with the connections of green chemistry and green engineering (Coish et al., 2018). The value creation of green initiatives is further supported by the results of a survey in 2009 of more than 1500 worldwide executives and managers about their perspectives on business sustainability (Berns et al., 2009). The study provided evidence that sustainability has the potential to affect multiple value creation levers over both the short- and long-term goals for the company. They found that six aspects are common to the notions of eco-green, sustainable, and environmental innovation. Those aspects are as follows:

1) Innovation object: Product, process, service, method.
2) Market orientation: Satisfy needs/be competitive on the market.
3) Environmental aspect: Reduce negative impact (optimum: zero impact).
4) Phase: Full life cycle must be considered (for material flow reduction).
5) Impulse: Intention for reduction may be economical or ecological.
6) Level: Setting a new innovation/green standard to the firm.

Company leaders with a vision that incorporates sustainability play a key role in ensuring that sustainability is part of the organization's creative process. Leaders and managers can create the value system of a company that can impact the type of innovation (e.g. incremental vs. radical) and the extent of innovation that is pursued by the company. The value-adding connections between the management of eco-innovation and the principles of green chemistry and green engineering are essential in creating a sustainable company. Sustainability and use of green chemistry should be of interest to business leaders, managers across various departments, innovation experts, sustainability officers, directors of research and development, product designers, engineers, and other people from across all disciplines who have an interest in business sustainability.

## 1.3 Green Engineering Definitions

Green engineering can be defined as a process to develop products, processes, or systems with minimal environmental impacts. The full product life cycle is developed when evaluating the environmental sustainability of the product, process, or system. Green engineering can be a foundation of sustainability. The 12 principles of green engineering are as follows (McDonough et al. 2003; Anastas and Zimmerman 2003).

1) Inherent rather than circumstantial
2) Prevention instead of treatment
3) Design for separation
4) Maximize efficiency
5) Output-pulled versus input-pushed
6) Conserve complexity
7) Durability rather than immortality
8) Meet need, minimize excess
9) Minimize material diversity
10) Integrate material and energy flows
11) Design for commercial “afterlife”
12) Renewable rather than depleting resources

Sustainable engineering is based on maximizing product throughput, quality, efficiency, productivity, space utilization, and reducing costs. Products are designed with inherently nonhazardous methods and nontoxic materials. Waste should be reduced at its source and not discarded after production. Production operations should be designed to minimize energy consumption and material use. Energy and materials should require a product requirement rather than a material input. Material and energy inputs should be based on renewable sources rather than from fossil fuel sources.

End-of-life options for the product should be designed at the beginning of a product life rather than at the end of it. The design goal should be product-targeted durability rather than product immortality.

Universal functionality should not be a design goal. Multicomponent products should be designed to promote disassembly and value retention. Integration and interconnectivity with available energy and material flows should be designed into products, processes, and systems.

Environmental engineering covers a wide range of applications of applying science and engineering principles to improve the natural environment of air, water, and land resources. Environmental engineering provides healthy water, air, and land for human use that is compatible with other organisms. It provides platform for balance between humans and other species on the planet. It also remediates environmental pollution issues. Recently, biological solutions to problems in environmental engineering often involve engineers integrating apparently disjointed biological knowledge, and tailoring this knowledge to address specific engineering challenges. The emerging discipline of environmental biotechnology contributes to the field of environmental engineering. Biological solutions help in assessing the risk to human health and determining the effectiveness of environmental engineering design decisions to reduce this risk to an acceptable level. Environmental engineers are helping waste water treatment plants to become more sustainable with the use of green engineering principles. Green engineering provides a biological solution to the problem of highly concentrated organic pollution in waste water treatment plants. In such waste water treatment plants, the processes of microbial degradation of organic waste with biomass production followed by sedimentation are encouraged to occur in a highly controlled environment. Alternative technologies for total nitrogen removal have been developed by environmental engineers that avoid some of the inefficiency of nitrification followed by denitrification (Oerther, 2005).

## 1.4 Sustainability Definitions for Manufacturing

Environmental aspects of product manufacturing include production of liquid and solid wastes, air pollution, water pollution, and GHG emissions. Discharges from manufacturing facilities can lead to pollution of the sewers, water treatment plants, and neighborhoods. Pollution prevention in communities with manufacturing operations can be achieved with regional sustainability programs that provide to small- and medium-sized manufacturing companies pollution prevention technical assistance and financial incentives to reduce pollution at the manufacturing sources rather than at the waste water and solid waste disposal sites (Granek and Hassanali 2006). Pollution often includes heavy metals, particulates, sulfates, phosphates, petroleum-based oils, solid wastes, oil-based inks and concentrates, and other contaminants. Sustainable practices can reduce the pollutants by installing filters, using water-based inks, bio-based oils, and recovery units for waste water effluent.

Sustainability can be defined in many ways for production companies to reduce GHGs and reduce pollution. Often missing from sustainability analysis, though, is waste generation. Products or services that are sustainable must also not produce significant amounts of solid or liquid waste. Sustainable products and practices should encourage the use of recycled materials during the production of products and processes and encourage the recycling of waste materials during the production of products and processes.

The essential components of sustainable products and services are ones with reduced GHG emission, reduced pollution, and reduced waste generation. Sustainable products, processes, and systems minimize the generation of GHGs, waste, and pollution. Thus, sustainable manufacturing incorporates producing products and processes with:

1) reduced GHGs emissions,
2) reduced solid waste, and
3) reduced pollution.

This definition will be used in subsequent chapters in the book. The first component of sustainable manufacturing processes is the reduction in GHGs. Reductions in GHGs can be done with lowering energy usage, which has direct cost reduction implications. Sustainable materials and processes minimize the generation of CO2eq gases. The second component of sustainable manufacturing is the reduction in waste generation. This can be listed for plastics manufacturing as the solid wastes are generated during the extraction of raw materials, production of the plastic pellets, and conversion of the pellet into plastic products. The listing of waste generation is listed as *kilogram of solid waste*. California in the United States has a law that requires state agencies and schools to achieve greater than 50% diversion rate of solid wastes (California Assembly Bill 939 2014), wherein over 50% of the trash that could be sent to landfill is sent to recycling, composting, or reuse. Reductions in waste generation can reduce the cost for manufacturing operations. Sustainable materials and processes minimize the generation of solid waste.

The third component of sustainable manufacturing processes is the reduction in pollution of air, land, and water. The pollution component can be defined in LCAs as creation of chemicals that cause eutrophication, acidification, and human health concerns.

Eutrophication can be defined as the addition of nitrates and phosphates to the land through the use of fertilizers and soil conditioners. Eutrophication is a very common pollutant from fertilizers in farming or from natural causes. Eutrophication can deplete oxygen in ocean and freshwater lakes causing algae and phytoplankton blooms in the water.

Acidification can occur in ocean and freshwater, as well as in soil when the pH is reduced due to the presence of sulfur and nitrous oxides. The presence of sulfur and nitrous oxides in the atmosphere can be released into the soil and waterways during rain storms. Sulfur and nitrous oxides are released during the combustion of fossil fuels at energy plants, burning of plastics as fuel, and during the combustion of fuels.

Toxic chemical pollution is caused by the presence of toxins that can cause human health problems, including cancer, blindness, sterility, and other health concerns. Combustion of fuels can lead to release of carcinogenic materials into the environment. Sustainable materials and processes reduce the release of pollution in the land, air, and water.

## 1.5 Life Cycle Assessment (LCA)

LCAs are an essential component of sustainability and can be used to scientifically determine the environmental effects of products, processes, and systems. LCA can be used to calculate the energy and raw materials consumed and the resulting carbon footprint, waste, and pollution generated in the production of a product or process. LCA is needed to establish the sustainability of products and processes because it follows a worldwide thorough approach to establishing measurable environmental outcomes of products and processes. LCA will be more fully explained in later chapters.

## 1.6 Lean and Green Manufacturing

Sustainability is an essential component of manufacturing today. Plastics manufacturing can lead the way in producing products with lower carbon footprint, lower waste, and lower pollution through the use of recycled and bio-based materials. Lean and Green are essential components of the manufacturing industry. Lean and Green manufacturing for plastics can be a unique feature of plastics manufacturers and can provide sustainable products for a promising marketplace.

## 1.7 Summary

Sustainable materials, processes, and systems must not compromise the ability of future generations to provide for their needs while providing for the needs of the current generation. The three components of sustainability have economic, social, and environmental aspects. Organizations are often analyzed with a “Triple Bottom Line” approach to evaluate the social, economic, and environmental performances of a company. The first aspect of sustainability can measure the impacts of products and processes on the society. The societal impact of using a material and manufacturing process can be measured by the effects on the population and the roles of the workers in the community.

The second aspect of sustainability can measure the economic impacts of using a material and manufacturing process to produce products. Sustainable manufacturing processes are defined as providing proper wages for the workers and clean and safe work environments.

The third aspect of sustainability can measure the environmental impacts of producing a product or system in terms of usage of natural resources for raw materials, energy, and real estate land. The production of plastic products can generate GHGs, solid and liquid wastes, air pollution, water pollution, and toxic chemicals.

Green chemistry principles can be used to develop chemical products and processes that reduce waste generation, energy, and production of toxic chemicals during the creation of chemicals. Green engineering principles are based on maximizing product throughput, quality, efficiency, productivity, and space utilization, as well as reducing hazards, pollution, and costs. Sustainable products, processes, and systems minimize the generation of GHGs, waste, and pollution. LCAs are an essential component of sustainability and can be used to scientifically determine the environmental effects of products, processes, and systems.

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