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Circular Plastics Economy: Redesigning Technology and Reimagining Society

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ABSTRACT

The UN Environment Programme has identified plastic waste as one of the urgent challenges of the 21st century and has set 2024 as the target date for the drafting of an international legally binding agreement on plastic pollution. While the concern for plastic pollution is justified, a workable solution that considers both the role that plastics play in society and the economy, and the scientific and technological challenges involved, will take a major global effort. The six thermoplastics that are most widely used today were not designed to be recycled. Likewise, over 10,000 chemical additives in plastics were not tested for their health and environmental safety. The complexity of plastic waste makes their effective management very difficult and uneconomic. A new system with two types of plastics is proposed: circular plastics that can be chemically reprocessed, and bio-based plastics that are designed for single-use and are biodegradable. This will require R&D into new plastics, as well as new standards and regulations. At the same time, R&D into the conversion of our current plastic waste into environmentally safe products must be undertaken. These will require a multi-sectoral approach which assigns responsibility to all sectors. Industry should institute extended producer responsibility and develop circular plastics. Society should adopt extended consumer responsibility. Government should replace its single-minded focus on GDP as the sole measure of development with the more holistic UN Sustainable Development Goals. This transition will not happen if it is seen only as a technological challenge. This transition will require a multi-sectoral approach which assigns responsibility to all sectors of society. We will not be able to reimagine plastics if we do not reimagine society.

Keywords: circular plastics, circular economy, single-use plastics, chemical additives, ocean plastic pollution, microplastics, extended producer responsibility, extended consumer responsibility

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Abbreviations: ASTM, American Society for Testing and Materials; EPR, Extended Producer Responsibility; GDP, gross do-mestic product; HDPE, high density polyethylene; ICCA, International Council of Chemical Associations; IUCN, International Union for Conservation of Nature; ISO, International Organization for Standardization; LDPE, low density polyethylene; LGU, local govern-ment unit; MRF, materials recovery facility; OECD, Organisation for Economic Cooperation and Develop-ment; PARMS, Philippine Alliance for Recycling and Materials Sustainability; PET, polyethylene tereph-thalate; PFA, perfluoroalkyl substances; PFC, perfluorinated compound; PP, polypropylene; PS, polystyrene; PTFE, polytetrafluoroethylene; PVC, polyvinylchloride; RIC, resin identification codes; SDG, Sustainable De-velopment Goal; SUP, single-use plastic; VOC, volatile organic compound; UNEP, United Nations Environ-ment Programme; WTE, waste-to-energy

INTRODUCTION

One of the urgent challenges of the 21st century is plastic waste. It has become a global challenge because plastic waste has now been found in virtually all corners of the world, as well as within our own bodies. We have failed to manage plastic waste, recycling less than 10% of the plastic that we produce. Meanwhile, most of the plastic products that we continue to use are not recyclable.

The United Nations Environment Programme has warned that: “It is time to change how we produce, consume and dispose of the plastic we use” (UNEP 2022a). The impact of plastics can be found in seven of the seventeen UN Sustainable Development Goals:

- SDG#6: Clean Water and Sanitation: Plastics are used by municipal water systems, by water stations and by people fetching water from the well.
- SDG#9: Industry, Innovation and Infrastructure: Plastics are necessary raw materials for many products; many of the devices of the 4th Industrial Revolution are made of plastics; plastics and polymers are used in construction; paints are polymers.
- SDG#12: Responsible Consumption and Production: Responsible consumption and responsible production are indispensable parts of the plastic product cycle.
- SDG#13: Climate Action: Most plastics are made from petrochemicals and burning plastics contribute to greenhouse gases. However, plastics also save energy because of its lighter weight.
- SDG#14: Life Below Water: It is the Decade of the Oceans and plastics have become ubiquitous pollutants in our seas and oceans.
- SDG#15: Life on Land: Plastics have overrun our landfills and are found wherever modern lifestyles are adopted.
- SDG#17: Partnerships to achieve the Goal: Any measure to address plastics requires partnerships because all sectors use plastics.

On March 2, 2022, the UN member states endorsed a historic resolution at the UN Environment Assembly to end plastic pollution and forge an international legally binding agreement by 2024. The resolution addressed the full lifecycle of plastic, including its production, design, and disposal (UNEP 2022b). At present, the UN has been focusing on ocean plastic pollution and the mismanagement of plastic waste (UN 2022). However, to solve the plastic waste problem, we need to have a comprehensive understanding of plastics, their role in society, and alternatives that are feasible.

Two strategies that have been gaining wide support are Extended Producer Responsibility (EPR) and circular materials, which are part of the move towards the circular economy. EPR aims to assign the burden of plastic waste to industry and circular materials challenge industry to develop plastics that are designed to be reused and recycled. Also, while most of the attention has been given to less than ten thermoplastics, there are many more plastics that are not being addressed. While in principle, EPR and circular materials appear to address the challenges of plastic waste, these may not solve the problem of microplastics.

Three important factors should be emphasized at the outset. First, because the Philippines is an archipelagic nation, the management of plastic waste should consider systems and technologies for small, isolated communities. Second, we should consider the entire plastic economy. To focus only on plastic waste is to use an end-of-pipe strategy which is not holistic. Plastics must be considered as a circular economy which means that plastic recycling must be recognized and supported as an essential industry. And third, any solution to the management of plastic waste must consider its impact on climate change, CO_2 emissions, and the UN SDGs.

This paper is a follow-up of an earlier paper on single-use plastic (Dayrit 2019). The objective of this paper is to propose possible strategies to solve the problem of plastic pollution by identifying the roles that industry, government and society should play. The principal advocacy of this paper is that we will not be able to solve the problem of plastic pollution unless we redesign plastics, as well as its use by society.

THE ROLE OF PLASTICS IN MODERN SOCIETY

Plastics define modern society. Plastics freed society from the limits of natural materials – such as wood, clay, ceramics, and metals – that had limited human activity. Plastics, with its affordability and designability, became ubiquitous and facilitated industrialization, globalization, urbanization, and consumption.

The first plastics were developed during the 2nd Industrial Revolution (mid-19th century to mid-20th century). These plastics were introduced as non-essential novelties, which later became important and iconic products, such as vulcanized rubber (1839, invention by Charles Goodyear), celluloid billiard balls (1868, to replace ivory), rayon (1891, substitute for silk), and Bakelite plastics (1907). Further breakthroughs in plastics brought new useful functionality: polyvinyl chloride (1920s, for electrical insulation, building materials), polyethylene (1930s, first used for electrical insulation), nylon fiber (1939, widely used during WW II), polyethylene terephthalate (1940s, used in the first synthetic polyester fabric, Terylene), polypropylene (1950s, for packaging and various equipment), and polystyrene (first introduced commercially in 1937 under the brand name Styrofoam®).

The 3rd Industrial Revolution, which occurred during the second half of the 20th century, saw the rise of analog and digital instrumentation, computer technology, and satellites. Plastics were used in all these technologies. The 1960s onwards saw changes in lifestyle. Consumer behavior was changed by the shift from the use of glass bottles, which were meant to be returned, to plastic bottles, which were meant to be thrown away (Bernat 2012). The iconic 1967 movie "The Graduate" endorsed plastic to the youth of the time with the famous advice: "There's a great future in plastics. Think about it." Plastics became embedded, both literally and figuratively, into the fabric of society.

The connectivity, increased functionality, miniaturization, and convergence of several technologies gave rise to the 4th Industrial Revolution, called 4IR, which is taking place today. Plastics have made 4IR possible. For example, plastics, such as Kevlar® (polyparaphenylene terephthalamide), Teflon® (polytetrafluoroethylene), Kapton®(polyimide), are used in satellites that enable global communication. Fiber optics are coated with Teflon. Plastics are used in flexible solar cells (poly(styrene sulfonate) films) and in high-performance lithium-ion batteries with plastic electrolytes.

The increase in plastic production from the 1950s to about 2018 is shown in Figure 1. The global production of plastic rose from 60 million MT in 1980 to 348 million MT in 2016 for an increase of almost six times while steel rose from 600 million MT to 1,700 million MT during the same period for a three-fold increase. During the same period, the global population increased from about 4.2 billion to 7.5 billion for an increase of 80%. Thus, there was a global *per capita* increase in plastic use of over three times. No other industry has experienced such growth (Chalmin 2019).

Packaging, which includes single-use plastic bags, is the main use of plastics, followed by building and construction, textiles, consumer goods, and automotive and electronics products. In 2015, the yearly average global per capita use of plastics was 46 kg. However, the amount of plastic used varies widely in different parts of the world: in South Korea and Canada, the per capita consumption of plastic is close to 100 kg; in the US, 80 kg; in Western Europe, 60 kg; in China, 45 kg; in India, 10 kg; and in Africa, 5 kg (Chalmin 2019). Today, as we realize the alarming rate at which plastic waste is destroying the environment, we need to consider both behavioral change and a new paradigm for plastic development, especially among societies that use a lot of plastics (Paterson 2019).

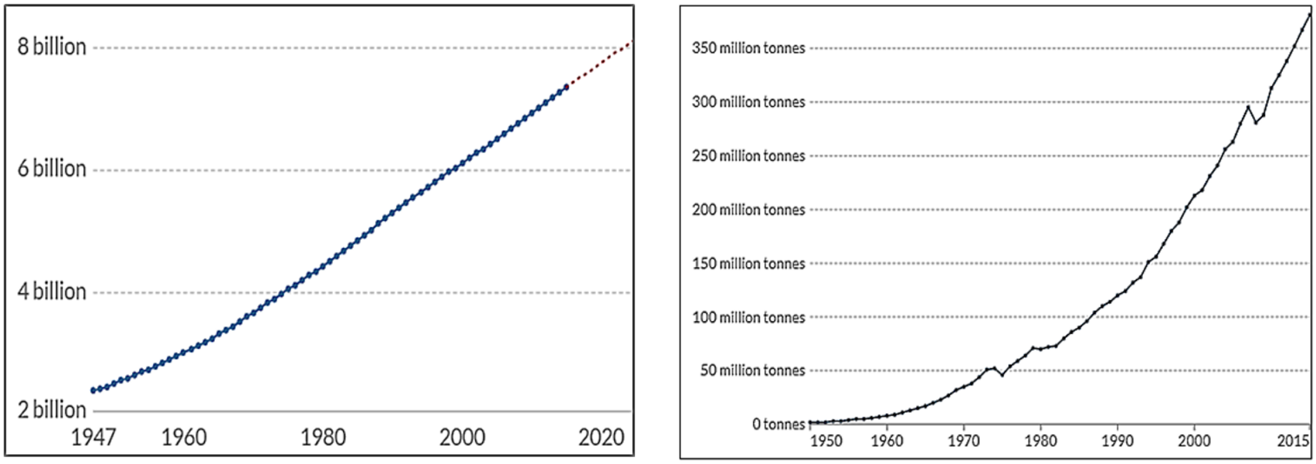


Figure 1. The increase in global population (left) and plastic production (right) from the 1950s to about 2018 is shown.
Source: UN Population Division, 2015 (left), https://ourworldindata.org/plastic-pollution right

COMPOSITION OF PLASTICS

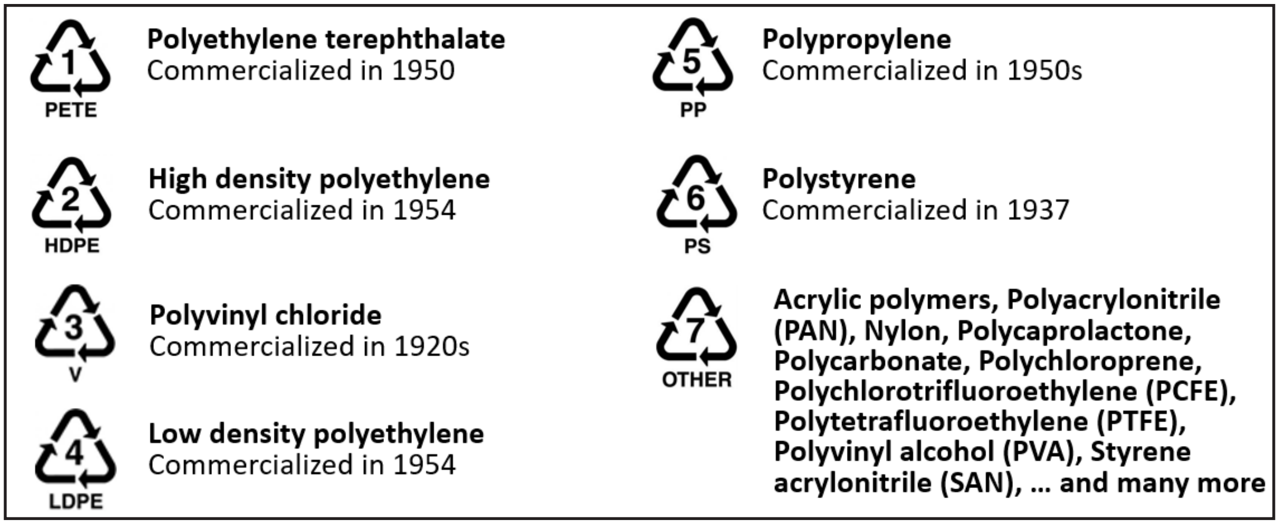
The demand for materials with specific design requirements led to the development of plastics with the desired properties. Today, there are thousands of types of plastics which are designed to meet specific applications. Plastics can be described by three characteristics: 1. Polymer composition: this includes the type of polymer, average molecular weight, and presence of co-polymers; 2. Additives: metals or compounds that modify the properties of the plastic to meet specific applications; and 3. Manufacturing process: various manufacturing processes, such as blow-molding and pressure, can produce plastics with different properties and this may affect the way by which the plastic waste is recycled (Evode 2021). For example, polystyrene can be made into different products by machining, extrusion, blow injection or foam molding. Unlike many manufactured products, much of this information is proprietary, and plastics manufacturers do not generally disclose specific composition, and health and environmental impacts (Wiesinger 2021).

Polymers are generally divided into two main types: thermoplastics and thermosets. Thermoplastics, which are made up of long chains of molecules, are pliable or moldable at elevated temperatures and solidify upon cooling. Thermoset plastics are chemically crosslinked and are generally used for rigid durable products. Because thermoplastics are used at higher volume, most of the focus has been on thermoplastics. But we must not lose sight of the problem of thermoset plastic waste, which may be more difficult to manage.

Resin identification codes (RIC)

Most of the thermoplastics that we use today were developed during the first half of the 20th century and came into wide use after WW II. The plastic pollution that resulted in the US was one of the drivers of the environmental movement of the 1970s. In response, the US Society of Plastics Institute introduced the resin identification codes (RIC) in 1988 to facilitate the identification of plastic waste: #1: polyethylene terephthalate, PET; #2: high density polyethylene, HDPE; #3: polyvinylchloride, PVC; #4: low density polyethylene, LDPE; #5: polypropylene, PP; #6: polystyrene, PS. To accommodate other plastics, #7: OTHER, was added as a miscellaneous category which included numerous types of plastics. (See Figure 2)

The US plastics industry lobbied to have the RIC codes officially recognized to push the message that plastics can be recycled, and that it was the consumers' responsibility to reduce, reuse, and recycle the plastic waste. However, there was no effort to reduce consumption; the reuse of plastics was left to the consumer; and there was no industry commitment to recycle plastic products (Romer 2021). Global data today show that only about 9% of plastic waste is recycled (Thiounn 2020). However, a recent OECD report projects that global plastic production may triple by 2060, while there will only be a



Polyethylene terephthalate
Commercialized in 1950

High density polyethylene
Commercialized in 1954

Polyvinyl chloride
Commercialized in 1920s

Low density polyethylene
Commercialized in 1954

Polypropylene
Commercialized in 1950s

Polystyrene
Commercialized in 1937

Acrylic polymers, Polyacrylonitrile (PAN), Nylon, Polycaprolactone, Polycarbonate, Polychloroprene, Polychlorotrifluoroethylene (PCFE), Polytetrafluoroethylene (PTFE), Polyvinyl alcohol (PVA), Styrene acrylonitrile (SAN), … and many more

Figure 2. The resin identification codes (RIC) are applied to thermoplastics. There are six defined resins (RIC#1 to #6) and one miscellaneous group (RIC#7). At present, only PET and HDPE are economically chemically recyclable.

marginal increase in plastic recycling capacity. The result will be a continued decrease in plastic recycling relative to production and an increase in plastic pollution (OECD 2022a).

Despite its limitations, the RIC triangle continues to be used today because a viable alternative is yet to be developed. The RIC is a voluntary ASTM International standard which is not harmonized internationally and is not officially adopted by all countries (Shamsuyeva 2021). Importantly, the American RIC system includes class #7, a miscellaneous group, which is of very little practical use. Table 1 details the global generation of thermoplastic waste by type of RIC polymer in 2015. It is notable that RIC#7 (OTHER) makes up the biggest group of plastic waste, while RIC#1 (PET), which is the most recycled type of plastic, is only the fifth.

This paper will be limited to the plastics covered by RIC #1 to #6 only. RIC #7 will not be covered because it is a large and ill-defined group. Mixed co-polymers will also not be included. The RIC plastics are all thermoplastics; the recycling of thermoset plastics is not included in this paper, but it is a complex group of plastics that must be managed.

Table 1. Global generation of thermoplastic waste by type of RIC polymer in 2015.

RIC Code	Estimated contribution to plastic waste, %*	Some applications
#7 OTHER	19 – 24	Automotive, boats, airplanes, fiber optics, construction, electronics, medical, others
#4 LDPE	18 – 20	Packaging, plastic bags, agricultural sheets
#5 PP	19	Packaging, automotive, pipes, bank notes
#2 HDPE	12 – 14	Toys, consumer bottles, pipes, houseware
#1 PET	7 – 11	Textiles, bottles
#6 PS	6 – 7	Packaging, construction, eyeglass frames
#3 PVC	5 – 10	Construction, pipes, insulation, hoses

Source: Chalmin 2018, Thunman 2019

Additives

Another major limitation of the RIC system is that it does not cover plastic additives. Chemicals are added to the polymer to prepare plastics of specific properties. The functions of these additives include adhesion promoters, antibacterial compounds, antioxidants, fillers and extenders, fire retardants, lubricants, pigments, plasticizers, stabilizers, and UV absorbers. The amount of each additive varies widely depending on the function of the additive, the type of polymer, and the intended use of the product. Phthalate plasticizers may be present from 10 to 70% of the weight of the polymer, while antioxidants may be present from 0.05 to 3% (Hahladakis 2018). Thus, the total amount of additives may range from 10 to over 70% of the weight of a plastic product. More than 10,000 additives, processing aids, and monomers are used and about 2,400 have been identified as potentially hazardous (Wiesinger 2021). Among the unregulated additives that have recently caused major concern are phthalates (plasticizers), bisphenol A (BPA, residual monomer of polycarbonates), and perfluoroalkyl substances (PFAS, resistant coating) (Table 2).

Because polymers are generally flammable, fire retardants are added from 3 to 25% by weight. Among the retardants used are polychlorinated or polybrominated compounds, phosphorous compounds, and metals, many of which are toxic (SpecialChem 2022). Plasticizers are added to impart flexibility to the plastic. Among the commonly used plasticizers are phthalates. The increase in the use of phthalates paralleled the growth of PVC during the 1930s (Graham 1973). Depending on the polymer and the use of the plastic, phthalates may make up 10 – 70% of the plastic by weight. Phthalates are now known as the “Everywhere Chemicals” because these compounds have been detected everywhere. Phthalates are hormone endocrine disrupting compounds that adversely affect the endocrine system and various organs. Phthalates have negative long-term impacts on the growth and development of children, as well as their reproductive systems (Wang 2021).

A class of compounds that has attracted considerable concern because of their widespread use and health and environmental impact are perfluorinated compounds (PFCs), also known as perfluoroalkyl substances (PFAS). PFCs are a group of organic compounds where the hydrogens have been replaced by fluorine. The first PFC which was discovered in 1938 was polytetrafluoroethylene (PTFE); this was later marketed as Teflon®. Their relative chemical inertness led to the development of over ten sub-groups of perfluorinated compounds PFCs have been developed into polymer products (e.g., Teflon and artificial blood), as well as plastic chemical additives, coatings, fire retardants,

Table 2. Various chemicals added to polymer resins to tune their functionality, improve their performance, and increase their value.

Chemical Additives by Category		
Adhesion Promoters	Fillers and Extenders	Processing Aids
Anti-Fogging Agents	Fire Retardants/Smoke Suppresants	Releasing Agents
Anti-Static Agents	Impact Modifiers	Silanes, Titanates, Zirconates
Antibacterials/Fungicides/ Mildewcides	Initiators	Slip and Anti-Blocking Agents
Antioxidants	Lubricants	Stabilizers
Bonding, Blowing, and Foaming Agents	Micas	Stearates
Coatings	Pigments, Colorants, and Dyes	UV Absorbers
Dispersants	Plasticizers	Viscosity Regulators

and plasticizers (Khan 2020). PFCs are used to coat numerous materials, ranging from stain-proof clothes, such as Gore-tex® fabrics and carpets, and common consumer products, such as pizza boxes and dental floss. However, their long degradation time have resulted in their continued presence in the environment; PFCs are now known as "Forever Chemicals". Some PFCs are now known to cause cancer, liver damage, metabolic disorders, among others (medicalnewstoday 2022). Recently, several papers have reported that it is possible to destroy PFAS chemically. For example, it was discovered that perfluoroalkyl carboxylic acids (PFCAs), a sub-class of PFCs, can be readily degraded using sodium hydroxide in mild polar aprotic solvents within 24 hours (Trang 2022). However, the challenge is how to recover all ofall the PFAS that is now in the environment.

CHALLENGES OF MANAGEMENT OF PLASTIC WASTE

Despite their universal use, plastics are the least regulated products. Their compositions, such as the specific polymer and the additives used, is not usually declared. Thus, their impacts on human safety and the environment are not known. For the same reasons, plastic wastes are difficult to recycle. Despite many efforts to recycle plastics, the very nature and diversity of plastics make recycling difficult and expensive.

One way of classifying plastic products is through their intended use: in particular, single-use plastic and durable plastic. This will also tend to divide the plastic types into thermoplastics and thermoset plastics.

Reduce, Reuse, Recycle

Despite the widespread use of the 3R logo, it was never implemented fully: there was no effort to reduce the consumption of plastics; the reuse of plastic products was left to individual initiatives of consumers; and the plastics industry did not really design their products to be recycled. Recycling faces numerous challenges. From the outset, recycling needs to overcome the inherent entropy of waste: energy is needed to collect, transport, segregate, and assess the suitability of waste plastic. A successful recycling system must consider each of these steps.

Today, confronted with mounting plastic waste and overflowing landfill areas, two modes of recycling have been developed: mechanical recycling and chemical recycling. Mechanical recycling of plastic refers to process by which plastic waste is shredded and heated without significantly altering the chemical structure of the polymers. The quality and characteristics of the mechanically recycled product depend on the quality and characteristics of the plastic waste. In principle, all thermoplastics can be mechanically recycled. Today, mechanical recycling is the most accessible and well-developed recycling mode in terms of industrial feasibility (Shamsuyeva 2021).

Chemical recycling, on the other hand, involves chemical reactions that break down the polymer structure to produce monomers and simple compounds to make new plastics or other chemicals. Chemical recycling could be a way around some of mechanical recycling's shortcomings. Chemical recycling yields monomers or polymers that are like the original feedstock. Chemical upcycling is achieved when the recycled product is of better quality than the original. The challenge of chemical recycling is its competitiveness in terms of quality and cost compared to virgin materials. Today, chemical recycling is being done on selected plastic wastes that are best suited to this process. Today, although LDPE and PP are also chemically recyclable, only PET and HDPE are economically recyclable and PVC and PS are not chemically recycled. The other option is mechanical recycling.

What is often overlooked with plastic recycling is that plastics contain various additives in undisclosed amounts, many of which have been shown to be harmful to health. (Table 2) Sometimes, plastic containers are reused to store toxic substances, such as oil and grease, gasoline, solvents, or pesticides. Heating of plastic waste, such as is done in mechanical recycling, may generate toxic VOCs due to additives and contaminant (Yamashita 2009). Plastic waste should be checked for volatile organic compounds (VOCs) and leachates before processing; recycled building materials should likewise be checked (Ansar 2021). True upcycling of plastic waste into products of higher value can only be done with clean plastic waste.

Single-use plastics

The European Commission (2019) defines single-use plastic (SUP) as plastics that are "used once, or for a short period of time, before being thrown away." However, this definition covers a wide range of uses, both essential and non-essential (Figure 3), as well as different types of plastic (Figure 4). This means that any regulation on SUP should be specific regarding the use and type of plastic. Right now, many regulations cover packaging and SUP bags of certain thickness. Bans on SUP bags generally cover LDPE, while bans on SUP packaging cover several plastics, such as HDPE, LDPE, PP, and PS. Figures 3 and 4 also highlight the fact that there are many types of plastics in use for both SUP and durable plastics, and that the same polymers are used in both groups. For example, thermoplastics such as PET, HDPE, PVC, PP, and PTFE, and thermoset plastics, such as rubber, epoxies, and cross-linked silicon materials, are used for both SUP and durables. Polyurethane is prepared commercially both as thermoplastic and cross-linked thermoset plastic. This makes recovery, segregation, and recycling more difficult. Due to this difficulty, we are addressing only a small group of SUP at the present time.

Recycling can be an effective way to recover material resources, but this depends on the material. The problem with recycling plastic lies with the material itself: there are thousands of different plastics, each with its own composition and characteristics. They include different chemical additives that makes chemical recycling difficult; the method of recycling depends on the type of plastic. Thermoplastics can be generally reused by the consumer for other household purposes. After recovery, sorting and cleaning, most thermoplastics can be mechanically shredded, melted and extruded, and be recycled into low-grade plastic applications. With extensive chemical processing, the monomers can be recovered, purified, and repolymerized and chemically recycled into new polymers. This is, however, an expensive and energy intensive process.

Plastic laminates are used in numerous kinds of packaging, such as sachets, flexible tubes, and blister packs for pills. These multi-component multilayer plastic packaging types are widely used in a wide variety of low-cost consumer products. However, they have become a major challenge for recycling because these are hardly reused and are very difficult to recover. Various industry attempts to recycle sachets have met with limited success; downcycling appears to be the most economical solution (Soares 2022). Alternative approaches include the use of returnable containers (glass or plastic) and refilling centers, reusable dishware, refilling for water and other consumer products.

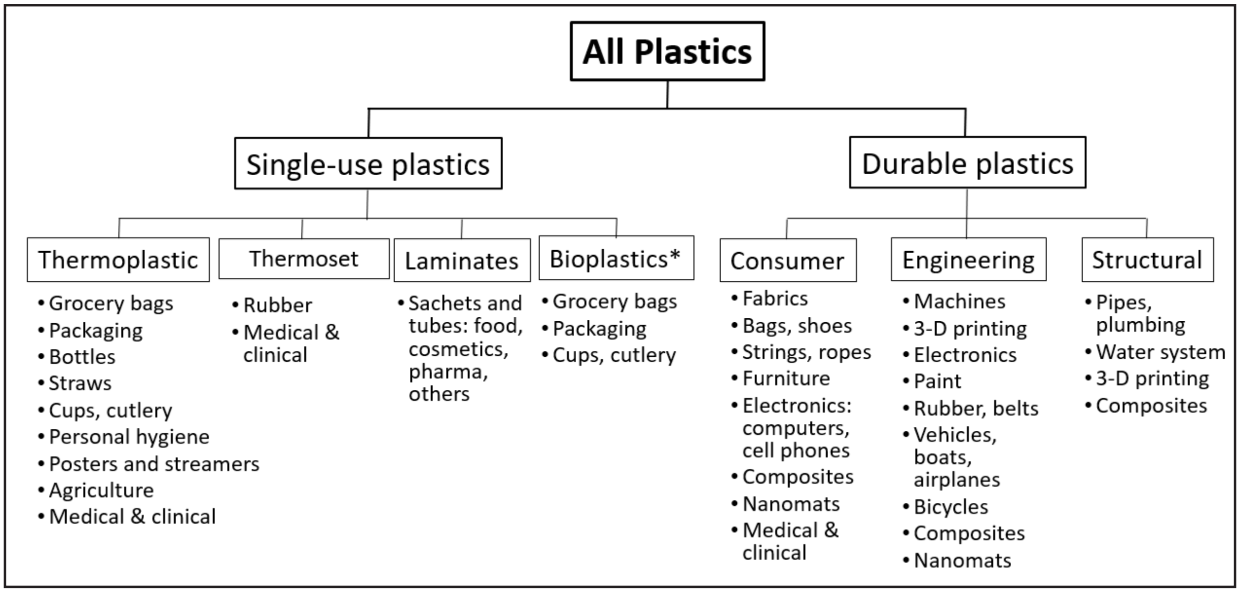


Figure 3. Single-use plastics (SUP) and durable plastics have different applications. To manage plastic waste, it is important to consider their applications.

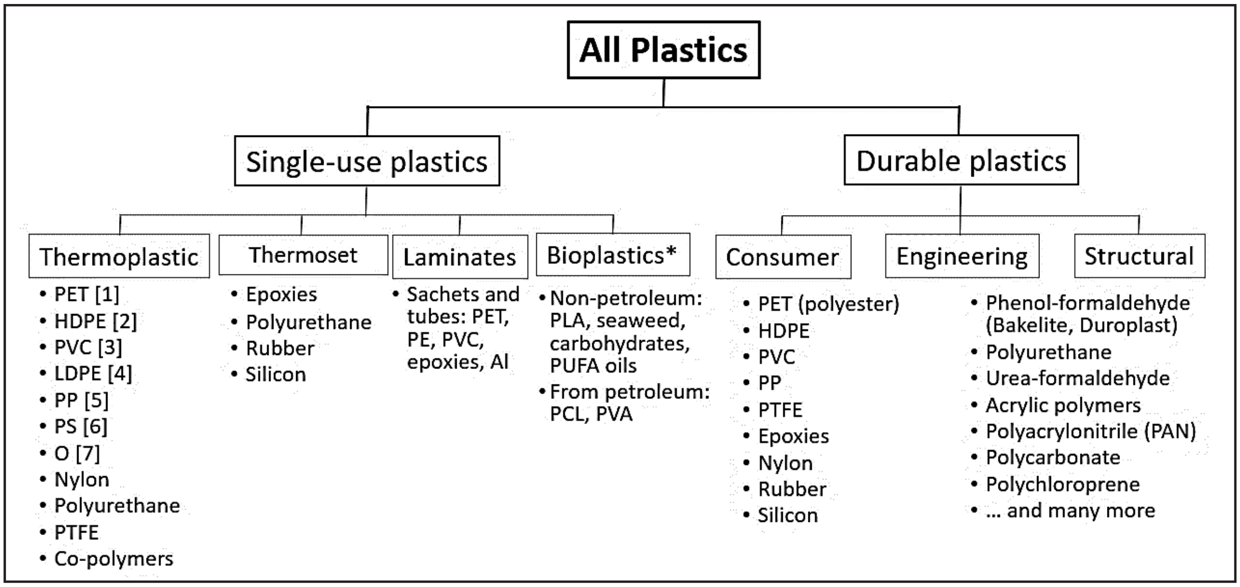


Figure 4. Single-use plastics (SUP) and durable plastics use different types of polymers. To manage plastic waste, it is important to know the polymer composition.

The OECD assessment report entitled “Global Plastics Outlook: Policy Scenarios to 2060” projected that recycling alone will not be able to meet the projected growth in plastic use and its attendant waste. The OECD urged that all countries must implement policies to curb plastics demand, increase plastic lifespans through repair, reuse, and recyclability, and improvement of waste management (OECD 2022b).

OCEAN PLASTIC POLLUTION AND MICROPLASTICS

One of the consequences of the mismanagement of plastic waste is ocean plastic pollution. Plastic pollution in the ocean ranges from large plastic sheets to microplastics. Large plastic sheets harm fish and other sea animals, as well as corals, while microplastics are ingested. The usual measurement of pollution is by weight. However, for large plastic sheets, the effect of physical size (area) has a bigger impact on ocean life than weight (Boucher 2019). Therefore, using weight alone as the basis for assessing impact on marine fishes and other organisms does not reflect the full impact of plastics in the ocean environment.

Ocean microplastics were first reported in 1957 by vessels which towed a continuous plankton recorder (CPR) as part of ocean surveys. The term “microplastic”, which was defined at this time as plastic particles less than 5 mm, originated from these ocean surveys (Ostle 2019). In 1972, larger pieces of plastic, about 0.25 to 0.5 centimeters in diameter, were collected in the Sargasso Sea in the western Atlantic (Carpenter 1972).

In 2004, plastic particles and fibers of micrometer size were reported and concerns for their health and environmental effects were raised (Thompson 2004). In 2015, UNEP defined plastic particles by their size as: macroplastics (>20 mm), mesoplastics (5-10 mm), microplastics (0.2-5mm), and nanoplastics (<0.2 mm). However, this does not include microfibers, which have been recently reported to be one of the main types of plastic particles in the ocean. In 2022, microplastics were found for the first time in Antarctic snow and it was estimated that their long-range air transport may be as far as 6000 km. Fibers were the most common morphotype and PET (polyester) was the most common polymer (Aves 2022).

In 2017, IUCN identified textiles and tires as leading primary sources of microplastic (< 5 mm size) in the oceans (Boucher 2017). However, Environmental Action, a Swiss-based consultancy group, estimated that paint is the biggest source of microplastic in the ocean (EA 2022). Such a claim may have some basis since paints, which are made of synthetic polymers, are very widely used. The paint and coatings industry represent a major global application of plastics. This industry is projected to grow by about 1.5 times from 2021 to 2029, driven by increasing demand in the construction, automotive, general industrial, and consumer markets (Statista 2022). It is a necessary technology that unfortunately produces microplastics.

Ocean microplastic pollution has attracted much attention due to the potential harm that such pollutants may cause to marine organisms and to humans who consume the fish. Numerous studies have suggested that these small plastic particles may cause complex and diverse detrimental health effects, from cancer (Gruber 2022) to obesity (Kannan 2021). The size, shape, chemical composition, surface charge, and hydrophobicity of microplastics may influence their toxicity.

SUSTAINABLE PLASTICS FOR A SUSTAINABLE SOCIETY

Focusing on the problem of plastic waste is an end-of-pipe approach which will not solve the problem. We need to start with the very design of the plastic material itself based on its intended use and consider the entire life cycle of plastics. Two groups of plastic are proposed: the first group are plastics that are designed as circular materials and the second group are bioplastics and biodegradable plastics which are meant for single use.

Circular plastics

Circular plastics are part of the circular economy. The ideal goal of circular plastics is to develop polymers and additives that are recyclable by design. Today, most of the discussion on circular plastics is focused on the existing polymer materials. Research is being undertaken to develop new polymer materials based on polyesters and reductive depolymerization and organocatalysts (Payne 2021). It should also be noted that less information is available regarding the development of safe chemical additives. Even with promising research results on new circular plastics, product development and commercialization will take several more years. In the meantime, research is focusing on how to make the existing thermoplastics more circular (Thunman 2019). Circular plastics, which are key to a circular economy, remain a major challenge.

Bioplastics and biodegradable plastics

Although the concept is attractive, there are no globally accepted definitions and standards for “bioplastics” and “biodegradable plastics” and characteristics such as “biodegradable” and “compostable”. To add to the confusion, many companies use these terms only to project a green image. For example, the term “bioplastic” has been used for plastics that contain biomaterials even though the amount is small. The term “bioplastics” has also been applied to thermoplastics that are made from petroleum (European Bioplastics 2018). Thus, not all materials that are called “bioplastics” are biodegradable. “Compostability”, a related process, implies that the resulting compost can be used in agriculture. However, if a bioplastic leaves behind toxic residues it would not be suitable for compost. Thus, a bioplastic may be biodegradable but not compostable (Kjeldsen 2019). Another point of ambiguity is whether the standard should apply to the biopolymer component or to the final bioplastic product, which may contain chemical additives which are toxic or not biodegradable. Given the growing demand for safe and environmentally sound bioplastics, globally accepted standards should be adopted.

There are numerous opportunities to make bioplastics from agricultural produce, agricultural waste, or by fermentation, using raw materials such as sucrose, vegetable oils, and seaweeds. However, to avoid competing with food uses, the utilization of agricultural waste, such as rice straw, sugarcane bagasse, coconut husk, and unutilized natural products, such as grass, have become attractive options (Caparino 2018). A particular advantage of the use of agricultural materials for bioplastics is its suitability for mechanical recycling, where the biomaterial can be processed by mechanical pulping and then coated to impart water- and grease-resistance suitable for disposable food use (Saini 2021).

RECOMMENDATIONS ON THE MANAGEMENT OF PLASTIC WASTE IN THE PHILIPPINES

In the Philippines, the management of plastic waste is included in the Ecological Solid Waste Management Act of 2001 (R.A. 9003) as stated in Section 15 (k): “Recycling programs for the recyclable materials, such as but not limited to glass, paper, plastic and metal.” This is the only mention of “plastic” in R.A. 9003. With the technical complexity of plastic, this law does not provide adequate attention regarding the management of plastic waste. R.A. 9003 stipulates that solid waste should be processed through a materials recovery facility (MRF). However, only 30% of local government units (LGUs) have MRFs where sorting and recovery of waste plastic can be done and less than 30% of LGUs have access to sanitary landfills (Business World 2021). This “end-of-pipe” approach has resulted in the mismanagement of plastic waste and overflowing landfills.

The Philippines, which has a very long coastline of more than 36,000 km, 421 rivers, and a coastal population of about 60%, faces significant challenges in preventing the discharge of plastic pollutants into the sea. A 2015 paper ranked the Philippines third in the world in terms of the amount of mismanaged plastic waste from people living within 50 km from the coast (Jambeck 2015), while a 2021 study ranked the Philippines first in plastic emissions into the ocean from river sources (Meijer 2021).

Two studies on Philippine river water samples showed significant presence of microplastics. Microplastics were detected in the water and sediment in the river and coastal waters in Batangas, as well as in the fish and oysters from these areas. The microplastics were in the shape of filaments, fragments, films, and pellets (Espiritu 2019). Another study that was done on five rivers that drain into Manila Bay showed that microplastics were present in all river water and sediment samples. Spectroscopic analysis from both studies identified the microplastic composition to be polyethylene, polypropylene, and polystyrene, which are the plastics that are commonly used in single-use plastic packaging (Osorio 2021).

The retrieval rate for different types of plastic waste depends on the economic value of the plastic. For thin plastic bags, polystyrene, and sachets, the retrieval rate is very low because of the very low value of the waste. In contrast, retrieval of PET bottles is estimated to be 90 per cent (Business Mirror 2018, GAIA 2019). Among the plastic waste that is collected, PET is the one that most commonly subjected to mechanical recycling.

In 2001, the Sentinel Company pioneered the use of thermal heating technology to convert plastic waste into chairs and benches (Envirotech 2018). In 2012, Marikina City converted styrofoam wastes into paving blocks for use in park beautification (PIA 2012). San Miguel Corporation first used recycled plastic in road building in the Philippines in 2019 (PNA 2019). The Philippine Alliance for Recycling and Materials Sustainability (PARMS), a private-sector led initiative to address plastic waste, has committed to address waste sachets. PARMS is supported by global and local corporations, plastic producers, recyclers, and other members of the waste value chain. In 2017, PARMS announced the construction of a P25-million facility that will recycle plastic sachets (Business World 2017). In 2020, PARMS introduced its “Zero Waste to Nature: Ambition 2030” program. Some malls have started collecting plastic waste for recycling into eco-bricks. The question is whether these initiatives will be enough to match the rate at which plastic waste is being generated.

With over 2 million square kilometers of water bodies within its exclusive economic zone and over 36 thousand km of coastline, the Philippines has a major stake in the quality of its marine resources. It is fitting that the NAST 30-year PAGTANAW 2050 has identified its main theme as a “Prosperous Archipelagic Maritime Nation” (NAST 2021). Plastic waste is a threat to marine sustainability.

The role of the LGU and the MRF

Figure 5 presents the scheme for plastic waste management from households and focuses on circular plastics, which can be reused, or processed using mechanical recycling or chemical recycling. The informal sector, including street vendors, microscale enterprises, and sari-sari stores, can be included in the category of households. The materials recovery facility (MRF) under the LGU separates and classifies the plastic waste. It can distribute or sell the plastic waste to various entities. The LGU can implement the EPR scheme in collaboration with the plastic producer. The Mandanas Ruling of 2022 which increases funding to LGUs should be used to strengthen plastic waste management programs (PNA 2021), such as the establishment of MRFs, technical training, and public education. Plastic waste produced by industrial, commercial, and institutional entities should be managed separately. Institutional entities include government agencies and schools.

The circular plastic would be labeled separately according to the type of monomer and additives used. The wastes of circular plastic would be collected separately, sorted, cleaned and may be mechanically

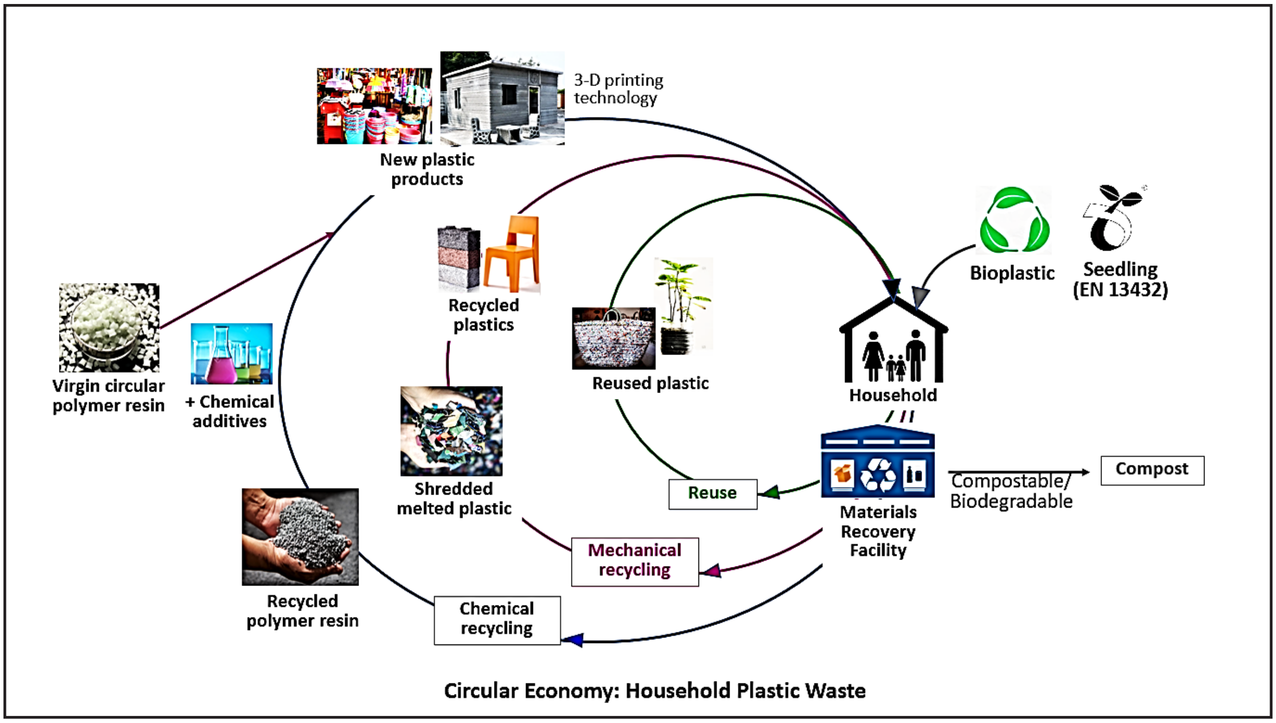


Figure 5. Proposed scheme for the management of household plastic waste. The materials recovery facility which should be managed by the LGU plays an important role in separating and classifying the plastic waste. The bioplastics are described in Figure 6.

or chemically recycled. Plastics must be redesigned to make them technically and economically recyclable: these are the challenges of circular plastics and a circular economy.

However, the limitations due to the nature of plastic materials will remain because organic polymers are not infinitely recyclable because the polymer chains will break down with each recycling eventually forming microplastics. In anticipation of this eventuality, the circular polymer and additives should be designed to be safe from the start.

Figure 6 presents the bioplastics and biodegradable plastics that can be used to make single-use plastic products. Since packaging accounts for close to half of the single-use plastic use, these applications should be the initial focus of bioplastics and biodegradable plastics. Although these wastes are expected to have a much smaller environmental impact, a waste management scheme should still be developed for these materials which can be directed towards composting. Properly done, composting can produce useful products (Ciriminna 2020).

Under this scheme, materials used for single-use plastic should be biodegradable, preferably from bio-based raw materials, such as lignins, sugars, and seaweeds. Because the demand for bioresources as raw materials may impose undue stress on the environment, biodegradable plastics from petrochemicals should also be developed. To ensure a sufficient supply of biomass for the production of bioplastics and to avoid a bioplastic vs. food situation, the base for biomaterials should be expanded, such as the use of waste plant residues and other ligno-cellulosic feedstock and improving the efficiency of industrial conversion of raw biomaterials into feedstock by using microorganisms and optimized physical and chemical processes (Issbrücker 2018). Recently, a high-performance resin-free bioplastic was developed from coconut husk. In this process, coconut husk fragments were directly processed into bioplastics through the partial removal of lignin, followed by hot-pressing. The coconut husk bioplastic showed good tensile strength, water stability up to 28 days of soaking, and microbial biodegradability (Leow 2022). With good R&D, it is possible to develop good bioplastics from our bioresources.

Figure 7 proposes a reconceptualization of plastics into circular plastics and biodegradable plastics. Under this scheme, plastics are classified according to their basic polymer characteristics which will facilitate their waste management.

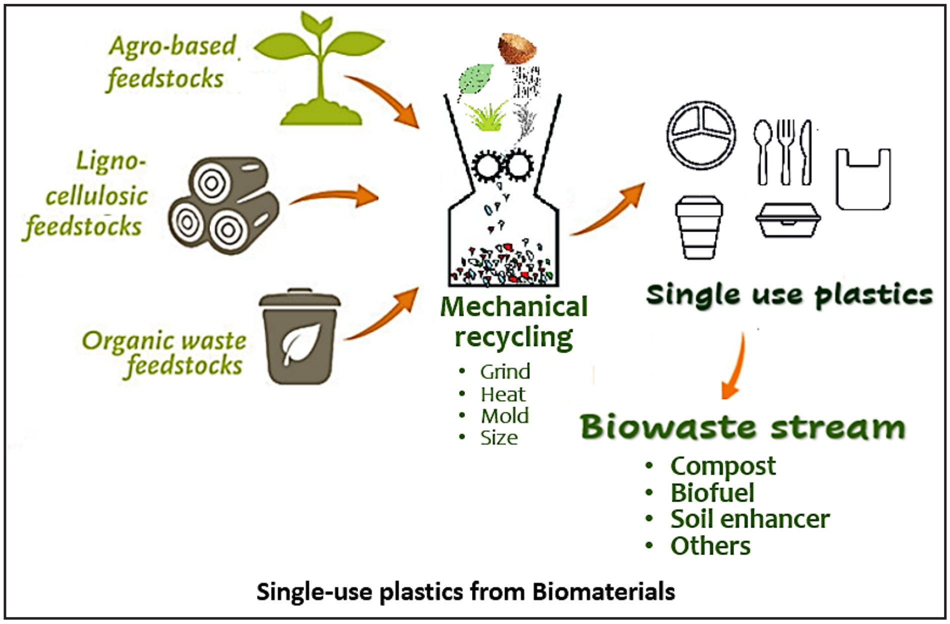


Figure 6. Single-use plastics, which are meant for short-term limited use, can be made by mechanical recycling of agricultural waste or other biomaterials. The waste stream from single-use plastic should be separate from circular plastics.
(Adapted from: https://www.european-bioplastics.org/how-much-land-do-we-really-need-to-produce-bio-based-plastics/)

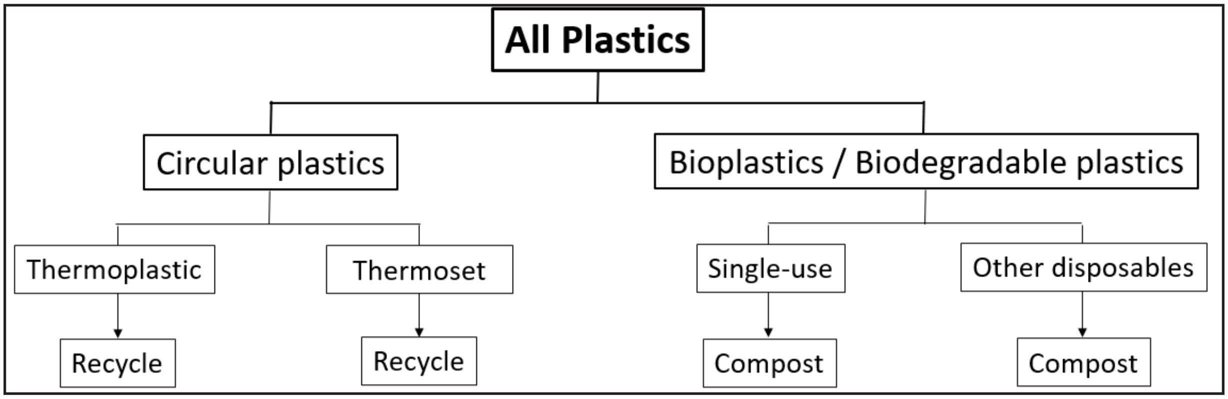


Figure 7. Plastics can be classified into circular plastics and bioplastics. New circular thermoplastics and thermoset plastics should be developed. Bioplastics and biodegradable plastics should be used for single-use plastics. Plastic waste from circular plastics and bioplastics should be managed separately.

To make circular plastics and biodegradable plastics a reality, considerable research is needed into circular polymers and biopolymers, as well as the needed safe chemical additives. Clear standards and supportive legislation are also needed for these new materials, in particular, for circular materials and biodegradation (Table 3).

Standards

Internationally enforceable standards are needed for the circular economy for circular plastics, biodegradable plastics, and chemical additives. Such standards should include a new set of agreed labels which will replace the 3Rs. Such standards should be developed and vetted by industry, government, international agencies, and recognized S&T institutions. There should be a monitoring system for compliance with the standards. Absent such standards and proper monitoring, there will be confusion and doubt regarding these new materials and the whole move towards sustainability and the circular economy. While there are ISO and ASTM standards for recycling of plastic, there are no standards yet for circular plastics. Both ISO and ASTM are industry standards which are often adopted by international agencies. The lack of international recycling standards and the lack of technology transfer by industry hinder the development of a global circular economy (Shamsuyeva 2021).

With the anticipated expansion of biodegradable plastics, it is important that standards for "biodegradability" be clearly set. The European Environment Agency (2020) listed three classifications of biodegradable plastics: biodegradable plastics, industrially compostable plastics, and home compostable plastics. The use of the several standards should be avoided as this is a cause for confusion. Biodegradation is a biochemical concept which integrates mass balance and reaction conditions and attempts to identify intermediates and byproducts. Levels of "biodegradability" can be established which can account for partial to complete biodegradation to CO2 and H2O, as well as nitrogenous products (NOx, NH3, urea, others), phosphorous and sulfur products, and other inorganic products (Muhayodin 2021). As a mass balanced biochemical reaction, biodegradability is independent of the process used and can be applied to any biodegradation method. In contrast, there are two systems used for compostability: industrial and home composting. Industrially compostable plastics are designed to biodegrade under well-defined conditions of an industrial composting plant, while home compostable plastics are designed to biodegrade under conditions of a home composter at lower temperatures than in industrial composting plants. Several European reference standards and national certifications have been established, such as DIN (Germany) and TUV (Austria), as well as separate certifications for biodegradation in soil, water and marine environments (EEA 2020). While the specificity of conditions for composting is necessary, the current system can become confusing for the consumer

Table 3. Standards, legislation, and other measures needed for circular plastics and single-use bioplastics and biodegradable plastics.

Circular Plastics	Single-use Bioplastics and Biodegradable Plastics
Standards for Circular Plastics	Standards for Bioplastics and Biodegradation
Life cycle assessment (LCA)	Life cycle assessment (LCA)
Extended Producer Responsibility (EPR)	Extended Producer Responsibility (EPR)
Extended Consumer Responsibility (ECR)	Extended Consumer Responsibility (ECR)
Require declaration of plastic composition	Require declaration of bioplastic composition
R&D on circular plastics	R&D on bioplastics
Research on environmental impact	Research on environmental impact
Develop circular economy	Develop sustainable bioplastic sources
Develop recycling system	Develop bioplastic waste management stream

and may hinder development of biodegradable plastics (Filiciotto and Rothenberg 2021). In the development of standards for biodegradable or compostable plastics, a single international system should be adopted, with levels to differentiate rates of biodegradation.

Life Cycle Assessment (LCA)

Life cycle assessment is a technique to assess the environmental impacts associated with all the stages of a product's life, from raw material extraction to materials processing, manufacture, distribution and marketing, use (and reuse), and disposal (or recycling), including the energy involved in each step. It is a cradle-to-grave analysis or cradle-to-cradle, in the case of recycling. LCAs can be used for different purposes, for example, to determine which products or processes might have the lower negative impact on the environment, or as a tool for eco-labeling (Muralikrishna 2017). The environmental impact of a plastic is assessed for its adherence to green design principles using metrics that include atom economy, use of renewable sources, biodegradability, percent recycled, health hazards during its life cycle, and energy use during its life cycle (Tabone 2010). LCA should be used to assess the various circular plastics and bioplastics that will be developed and compare these with our current plastics. LCA should be done to ensure that the new plastics that we are producing are better than the ones that they are replacing.

There have been initial attempts to consider the impact of micro- and nanoplastics in LCA, which consider particle size, polymer type, and shape. Uncertainties were noted regarding different types of polymers and species (Lavoie 2021). The impact of microplastics on the LCA of specific polymers and chemical additives needs to be further pursued.

Extended Producer Responsibility (EPR)

EPR is "an environmental protection strategy to reach an environmental objective of a decreased total environmental impact of a product, by making the manufacturer of the product responsible for the entire life-cycle of the product and especially for the take-back, recycling and final disposal" (Lindhqvist 1992). EPR is a complex scheme to implement because it requires identifying the responsible producer and tracking the plastic waste. The system has to consider the many products are internationally traded. EPR legislations in various countries have to be consistent and be implemented internationally as a trade measure. For plastic products, EPR entails the following:

- Product stewardship and liability: the producer takes responsibility for the environmental and health impacts of that product during different parts of the lifecycle of the product, including use, collection and disposal or recycling.
- Information: the producer should provide adequate product information to all involved parties of the product life cycle regarding safe handling, use, and environmental and health impacts. This should include declaration of plastic composition, including polymer type and additives (see below).

The implementation of EPR will be a challenge. In 2016, the World Economic Forum published a booklet entitled, "The New Plastics Economy: Rethinking the future of plastics" (WEF 2016). However, this WEF booklet focused mainly on plastic packaging only. The attention that the WEF gave to plastic packaging probably reflects the extent of use of plastics in packaging in international commerce and the challenge of implementing EPR on an international scale.

The International Council of Chemical Associations (ICCA) acknowledged the problem of plastic pollution and committed to transition to a non-toxic plastic circular economy (ICCA 2022). ICCA represents the leading chemical manufacturers and producers around the world, including the European Chemical Industry Council and the American Chemistry Council. ICCA member companies account for more than 90 percent of global chemical sales.

Extended Consumer Responsibility (ECR)

While there are consumer rights, there should be more attention to consumer responsibilities. Such responsibilities should be codified and become part of formal and public education. Four suggested components of ECR for plastics are:

- Public education: Knowledge is a prerequisite for a responsible consumer. Consumers should be well informed regarding plastics.
- Responsible purchasing: The consumer should

purchase with careful thought regarding the product, its intended use, and product life.

- Responsible use: The consumer should use the product properly until its useful life. Part of responsible use is the practice of second-hand sale and trade-in-for-upgrade arrangements (Sheu 2019).
- Responsible disposal: The consumer should dispose of plastic products properly. This includes segregation and options for reuse and mechanical and chemical recycling.

Declaration of plastic composition

Declaration of plastic composition is only required in special cases, such as plastics that come in contact with food or a declaration that the plastic product does not contain specific harmful additives. Such a declaration is needed for proper recycling of all plastic products.

Circular plastics in a Circular Economy

A circular economy can be defined as "an industrial system that is restorative or regenerative by intention and design... It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" (Ellen MacArthur Foundation 2013). The 73rd UN General Assembly recognized the importance of the circular economy in achieving the SDGs when it acknowledged a need for a "deeper understanding of the circular economy and how it can be leveraged to achieve the Sustainable Development Goals." (UN 2019)

A circular economy contrasts with the 'take-make-dispose' linear economy. Since material flows are part of the economy, a circular economy means that material flows should be circular as well. The OECD (2022b) has estimated that plastics lifecycle at present is only 8% circular and this is estimated to rise to only 14% by 2060 unless significant global policy changes are made.

A circular materials flow differs radically from the linear flow which takes raw materials from nature and disposes the waste to the environment. In 2015, the European Commission adopted its first circular economy action plan. The plan sought to close the loop of product lifecycles through greater recycling and re-use. For plastic products, the goal should be to develop circular plastics which can be chemically recycled after the product life. Unfortunately, such circular plastics are still in the research and development stage. So, at the present time, the circular economy is focusing only on improvements in recycling and not on developing new circular plastics. In February 2019, the EU-led Circular Plastics Alliance was formed with the participation of EU plastics companies. Notwithstanding the name of the alliance, the group committed – not to develop circular plastics – but recycle 10 million tons of plastics used in the EU 10 by 2025 (E.U. Circular Plastics Alliance n.d.).

Incineration and waste-to-energy (WTE) in a circular economy

The legality of incineration under the Philippine Clean Air Act of 1999 (R.A. 8749) was resolved by G.R. No. 147465. April 10, 2002, MMDA vs. Jancom Envt'l. Corp. *et al*. which stated that R.A. 8749 "does not absolutely prohibit incineration as a mode of waste disposal; rather, only those burning processes which emit poisonous and toxic fumes are banned." Following the spirit of R.A. 8749, the same criteria should apply to other modes of waste disposal which use thermal treatment, such as waste-to-energy (WTE). There are four major concerns regarding the use of incineration and WTE for plastic waste. First, is the concern for "poisonous and toxic fumes". For example, Japan, which disposes about 63% of its plastic waste through incineration and WTE, monitors the emissions from such plants using the same protocols as nuclear power plants. Second, incineration and WTE generates CO2. This should be considered in the overall national greenhouse gas emissions. Third, incineration still leaves waste behind in the flue gas, fly ash, bottom ash, and wastewater. A study on incinerators concluded that incineration is not the final solution of plastic waste since microplastics remain as waste products (Yang 2021). And fourth, for an archipelagic nation such as the Philippines where transportation of waste is expensive, consideration of incinerators should undergo LCA in comparison with other plastic waste management options in the context of a circular economy.

CONCLUSION

Plastics are considered as functional products that are discarded after use. However, plastics have become an enabling technology: they have facilitated the development of modern products, that have in turn characterized our 21st century lifestyle. We will not be able to solve the plastic waste problem unless it confronts the role of plastics in society.

The gross domestic product (GDP) of an economy is a measure of total production. Plastics have contributed to this growth in both direct and indirect ways. The direct contribution of plastics to global GDP can be measured by the growth of the plastics industry as well as consumer demand. However, the indirect contribution of plastics is significant, but difficult to measure. Because plastics enabled the development of so many modern technologies and products, it can be said that plastics are embedded in global GDP. And just as GDP has ignored the impacts of economic growth on the environment, so too have plastics ignored its impact of the environment. Today, even as there is evidence of the damage that plastics have done to the environment, the focus has remained on managing the leakages of plastic into the environment. This is an end-of-pipe approach.

Plastics should be considered holistically, from the source of raw materials to its design for performance, waste management, and recycling. Recycling should be recognized and developed as an enabling industry in a circular economy. However, if society is to achieve a circular economy, we must develop circular plastics. We are clearly far from achieving this. As a Nature editorial (2022) recently observed: “Circularity can only work if the link between a company producing more stuff and making more money is broken. Businesses need to be designed from the start (or redesigned) to be circular.” In other words, industry itself must learn to become profitable by being circular.

For the past several years, we have been focused on recycling only, with very poor results. In January 2019, the Alliance to End Plastic Waste was established by the world’s leading petroleum and chemical companies, which include BASF, Chevron Phillips Chemical, ExxonMobil, Dow Chemical, Mitsubishi Chemical Holdings, Proctor & Gamble and Shell (AEPW website). However, its recycling effort has faltered badly, achieving only 0.2% of its original target (Baker 2022). If the AEPW truly supports the establishment of a circular economy, it should prioritize the development of new circular plastics and a circular economy ecosystem. Otherwise, its recycling program will be seen as a diversion and a failure.

Plastics should be the concern of several agencies of government, such as the DENR, DTI, DOST, DA, DILG, and NEDA. The UN SDGs promote a more holistic set of criteria for development. The world will be able to address the problem of plastic waste at its core if the SDGs replace GDP as the criteria for progress. The circular economy – and circular plastics – as well as the other measures that have been proposed, such as extended producer responsibility, extended consumer responsibility, life cycle assessment, and others (see Table 4), will make sense only if the SDGs replace GDP.

The changes that are proposed in this paper will change the nature of plastics; it will also change many aspects of society. This transition will not happen if it is seen only as a technological challenge. This transition will require a multi-sectoral approach which assigns responsibility to all sectors of society. We will not be able to reimagine plastics if we do not reimagine society: plastics are us!

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None declared.

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