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Recyclable Plastics and Recycling Technology

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Abstract
Plastic recycling and recycling technology are essential facets of modern environmental stewardship, offering solutions to mitigate the detrimental impact of plastic waste on our planet. Plastic recycling involves the systematic collection, sorting, and reprocessing of discarded plastic materials, allowing them to be transformed into new products. This process serves multiple critical purposes, including the reduction of landfill reliance, the conservation of valuable resources, and the curbing of plastic pollution and associated greenhouse gas emissions.
Recycling technology plays a pivotal role in the efficiency and effectiveness of plastic recycling efforts. Innovative technologies such as automated sorting systems, advanced chemical recycling methods, and cutting-edge machinery have revolutionized the recycling landscape, enabling the extraction of greater value from discarded plastics.
Despite these advancements, plastic recycling faces significant challenges, including contamination issues, inconsistent recycling infrastructure, and varying rates of recycling across different regions. Addressing these challenges necessitates continued innovation, public awareness campaigns, and policy support to drive sustainable practices.
In conclusion, plastic recycling and recycling technology represent integral components of a sustainable future. Their continued development and widespread adoption are crucial for minimizing the environmental impact of plastic waste and promoting a circular economy where plastics are reused and repurposed, contributing to a cleaner and more eco-friendly world.

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I. Introduction

Most plastic simply cannot be recycled, a new Greenpeace USA report finds that U.S. households generated an estimated 51 million tons of plastic waste in 2021, only 2.4 million tons of which was recycled.

The annual production of plastic products globally was estimated at a staggering 440 million tons, as per OECD statistics. Considering the surge in online shopping, increased food packaging, and delivery due to the pandemic, it is speculated that plastic production in 2021 surged by approximately +16% compared to the preceding year. Correspondingly, the discharge of plastic waste was projected to escalate by +14.6% compared to pre-pandemic levels.

Within this plastic production cycle, an estimated 360 million tons of plastic waste are generated annually, with only a meager 13% undergoing proper recycling. The bulk of this plastic waste meets one of three grim fates: incineration (27%), landfilling (40%), or environmental dispersion. These methods, as underscored by a report, are viewed as "the worst disposal methods" from an environmental standpoint.

The core challenge of plastic waste management lies in its inherent non-biodegradability and the complexities of efficient combustion. Plastic, being a carbon (C) polymer, lacks the requisite oxygen for effective combustion, posing both environmental and potential health risks. Certain plastic types, such as PVC, containing chlorine, can release environmental hormones and carcinogenic substances when incinerated.

Moreover, landfilling exacerbates the problem due to plastic's non-biodegradable nature. Biodegradation, the natural decomposition of organic materials by microorganisms, is rendered ineffective by the strong molecular bonds in plastics, coupled with the presence of toxic additives inhibiting microbial survival. Consequently, the report emphasizes that plastic recycling transcends a mere moral obligation; it becomes an indispensable necessity for the survival of our planet, given the detrimental ecological and health implications of our current plastic waste disposal practices.

Recycling Technologies for Plastic Waste

Plastic recycling literally means "reprocessing plastic to make it usable again." After going through stages of production, distribution, and consumption, discarded plastic is collected and recycled through a specific process. Plastic comes in various materials such as PE, PP, PET, PVC, ABS, and even with the same material, its purpose can dramatically change based on processing methods and additives used. As a result, recycling plastic products is not easy, as it requires different techniques and processes depending on the material and application.

Recyclable Plastics

Polyethylene (PE): Polyethylene is one of the most common recyclable plastics and is found in various forms, including high-density polyethylene (HDPE) and low-density polyethylene (LDPE). It is used in items like plastic bottles, bags, and containers.

Polypropylene (PP): Polypropylene is used in products such as yogurt containers, bottle caps, and packaging materials. It is recyclable.

Polyethylene Terephthalate (PET or PETE): PET is commonly used in beverage bottles (e.g., water and soda bottles) and food packaging. It is recyclable and often used to make new plastic bottles.

Polystyrene (PS): Polystyrene is used in disposable cups, foam packaging, and some food containers. While it can be recycled in some places, it is less commonly accepted for recycling due to its low recycling rates.

There are three main methods for recycling plastic waste: "Mechanical Recycling," "Chemical Recycling," and "Thermal Recycling."

1. Mechanical Recycling involves processes such as sorting, packaging, cleaning, shredding, and blending to transform plastic waste into reusable plastic with its chemical structure preserved.
2. Chemical Recycling involves changing the chemical structure of plastic to regenerate raw materials.
3. Thermal Recycling, on the other hand, is an environmentally friendly process that efficiently converts plastic waste into thermal energy through controlled heating.

1. Mechanical Recycling

Mechanical recycling is processing plastics waste into secondary raw materials or products without significantly changing the material’s chemical structure. In principle, all types of thermoplastics can be mechanically recycled with little or no impact on quality.

Mechanical recycling is the most common approach used for recycling plastics like polyethylene terephthalate (PET) and high-density polyethylene (HDPE). PET and HDPE are typically used to make soft drinks bottles or containers, and are relatively easy to recycle.

Mechanical recycling refers to the processing of plastics waste into secondary raw material or products without significantly changing the material’s chemical structure. In principle, all types of thermoplastics can be mechanically recycled with little or no impact on quality. Mechanical recycling is the most widespread form of recycling and represents the majority of activity in Europe.

(1) Collection

Collection of end-of-life plastic products from separate and mixed waste streams

(2) First sorting

Once plastic waste arrives at the recycling plant, it is sorted. While some sorting may have taken place at the collection stage, further separation by color or thickness may be necessary.

(3) Shredding

Plastics need to be shredded into smaller pieces before they can go on for reuse.

(4) Washing

Washing removes dust and dirt to ensure plastics are clean before they go onto the next stage. This can include removing traces of food, drink or labels.

(5) Second sorting and control

Plastics are sorted again and controlled before being sent to extrusion.

(6) Extrusion

Plastics flakes are finally converted into homogenous pellets ready to use in the manufacture of new products

2. **Chemical Recycling Technology**

Chemical recycling does not require extensive separation by type and is less sensitive to contaminated waste. It also has advantages in terms of energy consumption compared to material recycling processes. It is mainly achieved through processes of thermal decomposition and chemical reactions.

For common plastics like polyethylene (PE), polypropylene (PP), and polystyrene (PS), chemical recycling involves thermal decomposition reactions or a combination of thermal decomposition reactions and chemical reactions using catalysts. This process can produce surfactant products that can be used as fuels or chemical raw materials.

Benefits of chemical recycling

Chemical recycling complements other plastic recycling options like mechanical, dissolution and organic recycling. Since it can deal with complex plastic waste streams, like films or laminates, chemical recycling can be used for plastic waste, which would otherwise result in incineration or landfill. With 67.5% of post-consumer plastic waste going to landfill and energy recovery across Europe, there is a clear potential for improvement.

Because chemical recycling breaks down polymers into their building blocks, it also allows the production of recycled plastic (recyclate) with virgin plastic properties that can be used in demanding applications, such as food contact.

3.**Thermal Recycling Technology**

Plastic waste is derived from petroleum and has a high calorific value, making it suitable for conversion into fuel. There are technologies for fuel conversion of plastic waste called 'Refuse Derived Fuel' (RDF) and 'Refuse Plastic Fuel' (RPF). Both RDF and RPF are renewable energy sources derived from combustible materials in waste. However, RDF is made from general municipal waste, while RPF is made from industrial waste such as plastic waste or wood, leading to differences in quality.

With the introduction of thermal recycling technology, even film materials like food packaging that were not previously recyclable can now be recycled. However, addressing the technological aspects of harmful emissions from incineration remains a necessary step.

The development of recycling technologies and products utilizing plastic waste is a global issue, and various research efforts are being made worldwide. The scope of application is expanding beyond everyday items like clothing, footwear, and bags to include electronics, pharmaceuticals, and even energy production. While using plastic products for convenience, it's important that we also focus on separating and recycling properly to help protect our planet.

Non-Recyclable Plastics

Polyvinyl Chloride (PVC): PVC is used in pipes, vinyl flooring, and some packaging. It is generally not recyclable due to the toxic byproducts released during recycling.

Polycarbonate (PC): Polycarbonate is used in items like eyeglass lenses and CDs. It is not easily recyclable due to its complex composition.

Polymethyl Methacrylate (PMMA or acrylic): PMMA is used in products such as acrylic glass (Plexiglas) and some automotive parts. It is typically not recycled in regular municipal recycling programs.

Polytetrafluoroethylene (PTFE or Teflon): PTFE is known for its non-stick properties and is used in cookware. It is generally not recyclable in household recycling systems.

Polyvinyl Chloride (PVC), Polycarbonate (PC), Polymethyl Methacrylate (PMMA or acrylic), and Polytetrafluoroethylene (PTFE or Teflon) are often considered non-recyclable or challenging to recycle for various reasons. Firstly, their chemical complexity sets them apart from more straightforward plastics like PET or HDPE, making it difficult to break down and recycle using conventional mechanical processes. These complex chemical structures hinder their recyclability.

Furthermore, many products made from these plastics can contain contaminants, coatings, or additives that complicate the recycling process and introduce impurities. For instance, PVC products often include plasticizers and stabilizers that hinder recycling and lead to impurities in the recycled materials.

Another challenge is their high melting points. PC, PMMA, and PTFE have relatively high melting points compared to common plastics, making them difficult to melt and reprocess without degrading their properties, resulting in reduced quality in recycled materials.

These plastics also tend to find niche applications, which can limit recycling demand. The specialized nature of their use means there may not be a significant market for recycled materials made from these plastics.

PVC, in particular, poses environmental concerns as it emits toxic chlorine gas when incinerated, discouraging its recycling through waste-to-energy or incineration processes.

Separating these plastics from other materials in the recycling stream is another challenge due to their similar appearances to other plastics or materials, leading to contamination that reduces the quality of recycled materials.

Finally, the lack of widespread recycling infrastructure for these plastics in some regions further contributes to their limited recyclability.

While there are some specialized recycling processes and technologies under development to address these challenges, they are not as accessible or widespread as those for more commonly recycled plastics like PET and HDPE. As recycling technology and sustainability efforts advance, there may be increased opportunities for recycling these challenging plastics in the future. However, currently, they are considered non-recyclable in many municipal recycling programs.

Biodegradable plastics and biodegradable synthetic plastics

"Biodegradable plastics" and "biodegradable synthetic plastics" are terms often used interchangeably, but they refer to similar concepts with some subtle differences in terminology:

1. Biodegradable Plastics:

Biodegradable plastics are a broad category of plastic materials that have the capability to break down naturally in the environment, typically through the action of microorganisms (such as bacteria and fungi) over time. These plastics can undergo decomposition and conversion into simpler compounds, like water, carbon dioxide, and biomass, under the right environmental conditions. Biodegradable plastics can be made from various sources, including natural materials (e.g., starch, cellulose) and synthetic polymers with special additives or modifications to enhance biodegradability.

a) Starch Based Biodegradable Plastics

These plastics are made from starch, a natural polymer found in plants. They are commonly used in packaging materials, disposable cutlery, and agricultural films. Examples include Mater-Bi and Novamont.

b) Cellulose-Based Biodegradable Plastics

Cellulose-based bio plastics are mainly derived from cellulose esters like cellulose acetate and nitrocellulose, which become thermoplastic upon modification. Celluloid is a well-known cellulose derivative.

c) Lignin Polymer Composites

Lignin polymer composites are aromatic compositions made from natural polymers that exhibit biodegradability. Lignin is derived from wood and other plant sources. It constitutes 20-30% of wood and consists of phenyl propane and benzene structures. It has a molecular weight of around 3000-10000 and is produced in large quantities as a byproduct in the pulp industry.

2. Biodegradable Synthetic Plastics:

Biodegradable synthetic plastics are a subset of biodegradable plastics that specifically refer to plastics made from synthetic (man-made) polymers with engineered properties to facilitate biodegradation. These plastics are designed to mimic the functionality of traditional plastics while having a reduced environmental impact because they can break down more readily when exposed to the right conditions. Biodegradable synthetic plastics include materials like polylactic acid (PLA), polyhydroxyalkanoates (PHA), polybutylene adipate terephthalate (PBAT), and others, which are produced through chemical processes.

a) PHA (Poly(Hydroxyalkanoate))

Some explanation about PHA was given in the previous article. Microorganisms synthesize PHA by limiting nutrient supply like nitrogen, oxygen, or other nutrients while providing excess carbon sources. The PHA granules can be recovered by breaking down the microorganisms. PHA is divided into short-chain length PHA (scl-PHA) with 3-5 carbon chains and medium-chain length PHA (mcl-PHA) with 6-14 carbon chains.

b) PLA (Polylactic Acid)

Polylactic acid (PLA) is derived from fermentation of starch obtained from corn, sugarcane, and other sources. PLA belongs to the family of heat-resistant aliphatic polyesters and is known for excellent biodegradability, biocompatibility, mechanical properties, and potential for blending with other materials. It finds applications in fields like biomedicine, packaging, and stationery. It's also important in drug delivery for applications like surgical rooms and implant materials.

Biodegradable Synthetic Plastics

Petroleum-based chemicals dominate the industry. Well-known synthetic polymers like PE, PP, PS, PET are widely consumed, but they are not biodegradable. However, the following synthetic polymers exhibit biodegradability. Biodegradable synthetic plastics are a type of plastic material that has been designed to break down and decompose in the environment, typically through natural biological processes, into non-toxic substances. These plastics are engineered to address the environmental concerns associated with traditional plastics, which can persist in the environment for hundreds of years and contribute to pollution.

It's important to note that the term "biodegradable" does not imply that these plastics will necessarily break down in any environment. The rate and extent of biodegradation can depend on various factors, including temperature, humidity, and the presence of specific microorganisms. Therefore, proper disposal methods and conditions are essential for these plastics to fulfill their environmental benefits. Some biodegradable plastics may require specific composting facilities or conditions to break down effectively.

Additionally, while biodegradable synthetic plastics offer environmental advantages over traditional plastics, they are not a panacea for plastic pollution. Proper waste management, recycling, and reducing overall plastic consumption are also crucial aspects of addressing the global plastic waste problem.

There are several types of biodegradable plastics.

a) PGA (Polyglycolic Acid)

Polyglycolic acid (PGA) is a heat-resistant aliphatic polyester synthesized by condensing glycolic acid (hydroxyacetic acid). The resulting polymer can be hydrolyzed into non-toxic glycolic acid monomers. This process is facilitated by esterases enzymes. PGA is used in medical polymers for applications such as surgical rooms. PGA is a biodegradable synthetic polymer often used in medical applications, particularly for absorbable sutures and tissue engineering. While PGA is biodegradable, its recyclability is limited and not typically included in standard plastic recycling programs.

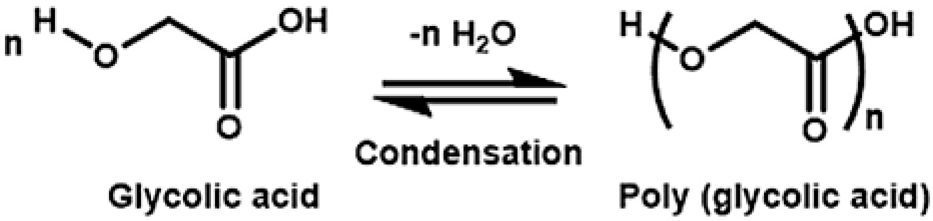

Figure 1. PGA

b) PBS (Poly(butylene succinate))

Poly(butylene succinate) or PBS is a biodegradable synthetic polymer that is used in various applications, including packaging, textiles, and agricultural films. It is similar in properties to PP and heat-resistant. It is synthesized through the condensation polymerization of succinic acid and 1,4-butanediol.

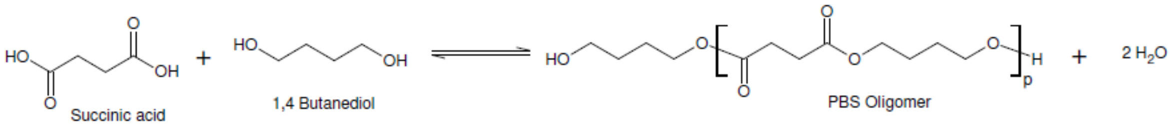

Figure 2. PBS

PBS is generally not compatible with conventional plastic recycling processes used for traditional petroleum-based plastics like PET and HDPE. Mixing PBS with these plastics can disrupt the recycling process and reduce the quality of recycled materials.

c) PCL (Polycaprolactone)

PCL is synthesized through ring-opening polymerization of ε-caprolactone. This polymer has a melting point of around 60°C and a glass transition temperature (Tg) of -60°C. PCL is important as a biocompatible material for implants. It has slower biodegradability compared to PLA. PCL is gaining popularity for applications requiring controlled drug release. It is used in surgical sutures and cosmetic surgeries. PCL is tough like nylon but exhibits putty-like properties at around 60°C, making it widely used in hobbies and crafts.

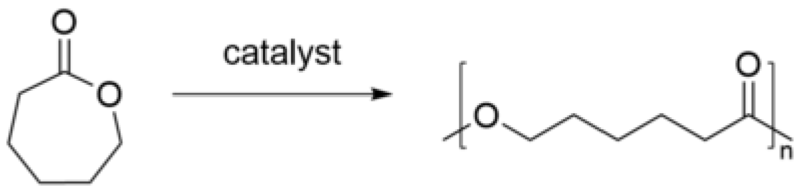

Figure 3. PCL

Polycaprolactone (PCL) is a biodegradable synthetic polymer often used in various applications, including 3D printing, drug delivery systems, and as a component in certain biodegradable plastics. While PCL is biodegradable, its recyclability is limited, and it is not typically included in standard plastic recycling programs.

d)PVA (Poly(vinyl alcohol))

PVA is a water-soluble vinyl polymer that exhibits biodegradability. It is primarily obtained by hydrolyzing polyvinyl acetate. It is used in applications such as food packaging, paper coatings, and fabric coatings. PVA has been used for a long time as the only vinyl polymer among biodegradable polymers.

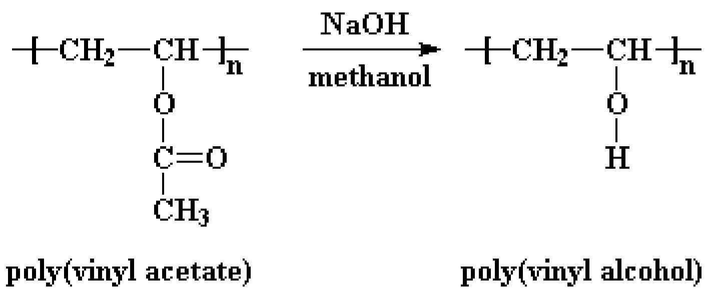

Figure 4. PVA

e) PBAT (Poly(butylene adipate terephthalate))
PBAT is a biodegradable polyester obtained by copolymerizing 1,4-butanediol with two types of dicarboxylic acids: adipic acid and terephthalic acid. It is also known as poly(butylene adipate-co-terephthalate). It shares characteristics similar to low-density polyethylene and is used in packaging materials, bags, and can be blended with other polymer materials.
The industrial manufacturing process of PBAT is somewhat unique. First, 1,4-butanediol is separately polymerized with adipic acid and terephthalic acid to synthesize two different polyesters. These polyesters are then subjected to an ester exchange reaction while in a molten state to produce PBAT. This reaction commonly employs tetra-n-butyl titanate (TBOT) as a catalyst.

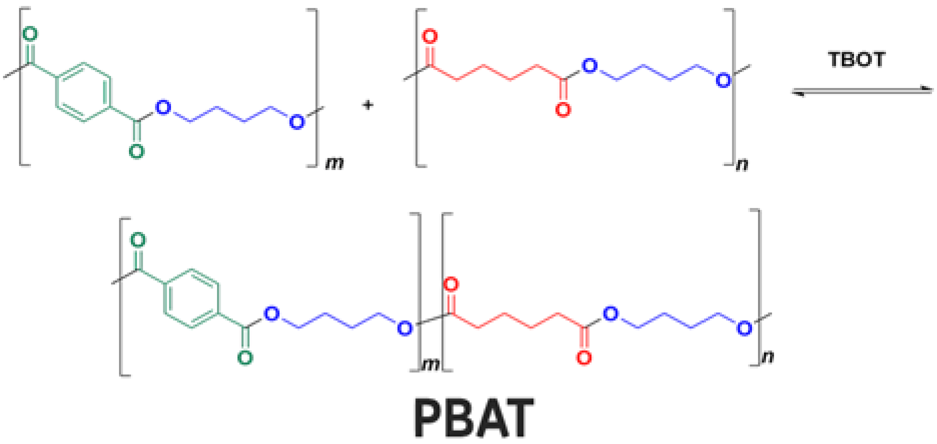

Figure 5. PBAT

Challenges of Biodegradable Plastics

It is said that plastic waste becomes biodegradable when it is broken down by microorganisms (such as fungi, bacteria) in the soil, mainly under anaerobic conditions, into carbon dioxide, water, and methane. If all plastic waste that threatens ecosystems were to become biodegradable, it is believed that it would significantly alleviate humanity's concerns.

However, the methane gas generated during biodegradation acts as a more potent greenhouse gas than carbon dioxide. Therefore, effective methods for capturing the generated methane gas need to be developed.

Another point of confusion is that the terms "biodegradable plastic" and "bioplastic" are not exactly synonymous. Polymers synthesized by microorganisms and some plants are commonly referred to as "biopolymers" or "bioplastics." Additionally, the term "natural polymer" is often used. Proteins, carbohydrates (such as starch and cellulose), and natural rubber produced within living organisms are considered natural polymers. Chitin, found in crab and shrimp shells, which is a polysaccharide of amino acids, also falls under the category of natural polymers. In other words, it's important not to confuse the classification based on the biodegradability of plastics with the classification based on their origin.

Composting of plastic waste is also a significant area of interest. If plastic waste can be composted and utilized beneficially in agriculture, it would be highly desirable. However, composting doesn't necessarily mean that a plastic is biodegradable. Composting plastic materials with the ability to compost requires strict control over various environmental factors such as high temperature, high pressure, and nutrient concentration. As a result, composting is typically carried out in large composting facilities. Additionally, composting generally occurs in aerobic environments, which distinguishes it from anaerobic biodegradation.

For example, PLA is a polymer that can be composted. In a narrow sense, it isn't strictly biodegradable. PET produced by certain bacteria has the same chemical structure as petroleum-based PET, and even though it's a bioplastic, it doesn't possess the same level of biodegradability. In other words, not all bioplastics are inherently biodegradable.

In summary, "biodegradable plastics" is a broad term encompassing all types of plastics that can biodegrade to some degree, whether they are made from natural or synthetic materials. "Biodegradable synthetic plastics" specifically refer to synthetic polymers that have been engineered for biodegradability, making them a more environmentally friendly alternative to traditional plastics. Both types of plastics aim to address the environmental concerns associated with plastic pollution by breaking down more easily in the environment compared to non-biodegradable plastics. However, it's important to note that the effectiveness of biodegradation can vary depending on factors such as the type of plastic, environmental conditions, and the presence of specific microorganisms.

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