Novel Trends in Plastic Waste Management

Mrs. Fabena P V

Assistant Professor (Ad-hoc), Department of Chemistry,

KAHM Unity Women's College Manjeri, Calicut University

***Email**: febina555@gmail.com*

Introduction

The contemporary era faces a widespread challenge in the effective management of municipal solid wastes (MSW). The accumulation of these waste materials has led to various environmental issues, ranging from the regular release of greenhouse gases to the scarcity of available space for waste disposal. The adverse environmental impacts have sparked growing concerns among the public, prompting political measures and legislation aimed at minimizing the introduction of waste into the environment. In response to these challenges, efforts have been directed towards implementing solutions that promote sustainable waste management. Central to these initiatives is the encouragement of municipal solid waste (MSW) recycling and the efficient conversion of waste materials into energy and other valuable chemicals. The objective is to not only reduce the environmental footprint associated with waste but also to harness the potential energy and resources embedded in these materials.

Conventional methods of plastic waste management

Conventional methods of plastic waste management have been integral in addressing the persistent environmental challenges posed by the increasing accumulation of plastic waste. Some of the conventional methods include

A) Landfills are one of the most common conventional methods for plastic waste disposal. Plastic waste is transported to designated landfill sites, where it is deposited and compacted. Landfill disposal poses environmental risks, including soil and groundwater contamination. Plastics can take hundreds of years to decompose, contributing to long-term environmental impact.

B) Incineration involves burning plastic waste at high temperatures, converting it into ash, heat, and gases. The heat generated can be used for energy production. Incineration releases greenhouse gases and pollutants, contributing to air pollution. It also raises concerns about the potential release of toxic substances from burning plastics.

C) Mechanical recycling is a process where collected plastic waste is sorted, cleaned, melted, and reprocessed into new products. Mechanical recycling is limited by the need for strict separation of plastic types, contamination issues, and the degradation of plastic quality with each recycling cycle.

D) Encouraging the reduction of single-use plastics at the source and implementing plastic bags are strategies aimed at minimizing the generation of plastic waste. Implementation challenges, resistance from industries, and the need for viable alternatives can hinder the effectiveness of source reduction and bans

. E) Collection and Manual sorting involve collecting plastic waste, manually sorting it based on types and recyclability, and then sending it to recycling facilities. Labor-intensive sorting processes can be time-consuming and may not be entirely effective, leading to the inclusion of contaminants in recycling streams.

While these conventional methods play a role in managing plastic waste, the limitations and environmental impacts associated with some of these approaches highlight the need for continuous innovation and the adoption of more sustainable and advanced methods in plastic waste management.

Advanced Non-biodegradable Plastic Waste (NPW) Technologies

The technologies are introduced based on basic classification into two strategies: recycling and degradation. Recycling technologies are further categorized into three subtypes: physical recycling, energy recovery, and resource recovery. Degradation technologies are further categorized into two subtypes: biodegradation and oxo-biodegradation. Oxo-biodegradation is divided into abiotic degradation and biotic degradation. Abiotic degradation includes photodegradation, thermos degradation, mechanochemical degradation and other degradation techniques.

Recycling Technologies:

Recycling disposal methods can be further classified into various subtypes according to technical characteristics. The American Society for Testing and Materials (ASTM) standard D5033-(2000) divides recycling into four categories: primary recycling (mechanical reprocessing of scrap materials with properties similar to those of virgin plastics, named ASTM I), secondary recycling (mechanical reprocessing of used materials into products with fewer performance requirements, named ASTM II), tertiary recycling (recovery of valuable chemical intermediates in the form of gases, liquids, and even solids, named ASTM III) and quaternary recycling (recovery of the energy content of plastics by incineration, named ASTM IV) (Okan et al., 2019).

Primary recycling and secondary recycling involve mechanical reprocessing of used materials into products with little or no effects on their physical properties, which can also be considered physical recycling. Tertiary recycling involves valuable chemical intermediate recovery, while quaternary recycling involves energy recovery, which can be seen as resource recovery and energy recovery, respectively.

A) Physical recycling of NPW

This includes direct reuse, extrusion, segregation and so on. Resource recovery includes thermolysis (pyrolysis, gasification, hydrocracking) and chemolysis. Energy recovery usually refers to incineration. Due to the growing environmental problems associated with NPW, recycling methods have received widespread attention due to their environmental friendliness and economic benefits.

B) Energy recovery of NPW

More importantly, recycling methods can recover abundant valuable products such as fuels and oil. This is consistent with the theme of sustainable development advocated by countries worldwide. According to a previous report, recycling 1 ton of plastic waste will save up to ~130 million kJ of energy. The annual energy savings from recycling all global plastic waste is equivalent to 3.5 billion barrels of oil, valued at approximately $176 billion. The calorific values of PE, PP and PS are very similar to those of conventional fuels illustrating that polyolefin plastic is the most effective plastic for energy recovery from a calorific point of view. The main incineration product of carbon dioxide and water further makes it possible to replace conventional fuels. The calorific values of PVC, PET, and PA are much lower, and thus, these materials are not suitable for incineration. PVC can even generate toxic gases such as HCl that corrode equipment.

C) Resource recovery of NPW

In addition to energy recovery and mechanical recycling, obtaining valuable petrochemicals or monomers from NPW is attracting increasing attention. This is deemed resource recovery. NPW can be treated to generate a mixture containing a variety of hydrocarbon components for use as fuel. For example, polyethylene (PE) has been considered a promising feedstock for fuel (gasoline) and value-added products such as synthetic lubricants.

Resource recovery from NPW is mainly realized via thermolysis. During thermolysis, polymers, which are the major component of plastic, undergo chain scission to produce low-molecular-weight compounds and monomers. Pyrolysis, hydrocracking, gasification are different types of thermolysis technology.

In addition to thermolysis, chemolysis is another resource recycling technology. Chemolysis is also referred as solvolysis or depolymerization. Chemolysis of plastic is a process in which individual plastics can be chemically treated or depolymerized into monomers. The chemolysis reaction routes mainly include glycolysis, hydrolysis, methanolysis, and alcoholysis.

Degradation:

The technologies designed for resource and energy recovery exhibit characteristics of high energy consumption and extensive equipment requirements. Additionally, a significant drawback is that many of these technologies generate additional byproducts that are either toxic or nonrecyclable, persisting in the environment for extended periods. These challenges have prompted the exploration of alternative technologies for the degradation of non-recyclable plastic waste (NPW), each showcasing distinct advantages.

Ideally, the ultimate goal is to achieve degradation products of plastics in the form of carbon dioxide (CO2) and water (H2O). In contrast to traditional recycling methods, the degradation of plastics doesn't necessitate harsh conditions such as elevated temperatures and pressures. This deviation makes the degradation of NPW a more environmentally friendly and non-hazardous approach to waste management.

Degradation, as the name implies, in this strategy where NPW undergo a series of degradation processes eventually converted to carbon dioxide and water, which are released into the environment. The microbial degradation of plastic has attracted much attention due to its advantages of low energy consumption, complete degradation, and environmentally friendliness However, plastics people used are non-biodegradable in most cases.

To reverse this adverse situation, a large number of advanced technologies have been applied to pretreat nonbiodegradable plastics to increase their degradability by microorganisms. Mainstream pretreatment technologies can be classified into four categories: photodegradation, thermodegradation, mechanochemical degradation, and other degradation. These pretreatment technologies are combined with subsequent biodegradation treatment to achieve oxo-biodegradation.

Classifying degradation technologies into two types, biotic and abiotic, reveals distinct characteristics. Biotic technology exhibits a slow degradation rate, whereas abiotic technology operates at a faster pace. However, relying solely on abiotic technology for plastic degradation is hindered by its high energy consumption, making it unsuitable for addressing plastic pollution. Consequently, there has been substantial research interest in combining these two technologies, aiming to leverage their respective advantages and address the challenges associated with plastic waste management.

The predominant focus of research on abiotic technology lies in its impact on the physical and chemical properties of plastics rather than the mineralization rate. This emphasis aims to enhance the biodegradability of plastics by altering their inherent characteristics. In this review, degradation technology is categorized into biodegradation technology and oxo-biodegradation technology. The former utilizes microorganisms or other organisms to break down plastics into carbon dioxide and water. In the latter, the polymer undergoes various abiotic predegradation processes, such as photodegradation and thermal degradation, before being broken down into small-molecule substances. These substances can be easily degraded by microorganisms or other organisms, ultimately converting them into carbon dioxide and water. The latest trends in degradation technology include:

A) Biodegradation of plastics

The biodegradation of plastic is an environmentally friendly treatment that does not generate any by-products. Biodegradation of plastic is a process in which plastics or polymers are broken down by living organisms or microorganisms, e.g., invertebrates, bacteria, fungi and even algae . The end products of this process are CO2, H2O or another non-hazardous biomass.

B) Oxo-biodegradation

The degradation of plastic by microorganisms or invertebrates is challenged by the polymer's structure, long chains, and the presence of additives like antioxidants. Achieving complete degradation in a short time is difficult due to these factors. Consequently, plastic requires pretreatment to predecompose the polymer into forms more accessible for microorganisms. Oxo-biodegradation, extensively researched, employs a two-stage process: abiotic oxidation and biotic degradation. The initial stage utilizes techniques like photodegradation and thermal degradation to oxidize the plastic. In the subsequent stage, microorganisms biodegrade the plastic products generated in the first stage. Studies indicate that the efficiency of the abiotic degradation stage significantly impacts the overall efficiency of oxo-biodegradation. The unique property of the oxo-biodegradation process, combining abiotic and biotic technology, not only significantly reduces the time required for plastic microbial degradation but also facilitates the transformation of plastics into harmless products. This makes oxo-biodegradation a crucial and contemporary NPW treatment technology.

C) Photodegradation

Photodegradation is a process where polymers decompose by absorbing energy from light, generating free radicals, and in the presence of oxygen, it is known as photooxidative degradation. The primary light source for photodegradation is near-UV-range light (290-400 nm). Near-UV-range light, with its high energy, can cleave the C-C bond of the polymer chain. Photodegradation stands out among degradation technologies due to its unique advantage — the ability to spatiotemporally localize and control light in a facile, green, and independent manner This technique not only utilizes sunlight to degrade plastics in nature but also reduces the subsequent biodegradation time, offering the potential for complete plastic degradation.

D) Thermo degradation of plastic

It is important to highlight that thermos degradation should not be confused with pyrolysis. The primary distinction between these two methods lies in their distinct purposes: pyrolysis is geared towards fuel recovery, such as gasoline, while thermos degradation is intended to enhance subsequent microbial degradation by breaking down macromolecular polymers into small-molecule products. Unlike pyrolysis, thermos degradation typically takes place in the presence of oxygen, and the reaction temperature is lower than that required for pyrolysis.

E) Mechanochemical degradation of plastic

Mechanochemical degradation of polymers entails degradation induced by mechanical stress under strong ultrasonic irradiation. In this unique process, the polymer undergoes high vibrations, essentially experiencing a mechanical force. As ultrasonic waves traverse the solution, polymer chains undergo breakdown through sheer and mechanical forces. Chemical reactions induced by radicals further contribute to the process, ultimately leading to a reduction in molecular weight.

Other techniques for NPW treatment involve the generation of reactive oxygen species (ROS). These methods utilize reagents like ozone, the Fenton reagent, and other potent oxidant agents, such as persulfate. Consequently, the easy production of ROS is a key aspect of these degradation techniques

Conclusion

The management of plastic waste is undergoing a transformative phase, with novel trends offering promising solutions to the global challenge. From circular economy strategies to advanced technologies and changes in consumer behavior, a multi-faceted approach is essential. Collaborative efforts between governments, industries, and individuals are crucial to realizing a sustainable and effective plastic waste management ecosystem. Adopting these new trends in plastic waste management can lead to a more sustainable and environmentally friendly approach to the production, use, and disposal of plastics. These initiatives contribute to reducing plastic pollution, conserving resources, and promoting a more circular and responsible approach to plastic use in various industries.

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