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Recent advances in plastic waste recycling via valorisation: A review

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Abstract
Plastic, commonly known as a synthetic polymer, is used in a diverse range of applications on a large scale. It is considered one of the most important and widely used materials in the world today. However, as the global production of plastic increases, so does the amount of plastic waste generate. Plastic waste has become a global environmental concern due to its persistence in the environment, causing various issues, including damage to wildlife, and contamination of soil, air, and water resources. As a result, researchers have looked into different techniques for handling plastic waste in an environment-friendly manner. Plastic valorisation is an important aspect of waste management that presents an opportunity to reduce plastic waste and its negative impact on the environment. As the problems associated with plastic waste continue to increase, continued research into innovative solutions for plastic valorisation is crucial. With the recent advances in chemical recycling, mechanical recycling, biodegradable plastics, and utilization of plastic waste resources, there is growing hope for a sustainable future. The development of new plastic waste valorisation technologies holds significant promise for the future, and continued research and development will drive the global adoption of plastic valorisation in waste management.

Keywords: Plastics, valorisation, environment, waste utilization, waste recycling

Introduction

Polymers are long chains of monomers that are clung to other indistinguishable subunits to form a polymer that can be conveniently moulded from one shape to another based on their desired functionality [1]. Plastics are primarily composed of binders, fillers, pigments, plasticizers, and other additives, the binder gives plastic its primary properties, and commonly, its name is also based on binder molecules. Binders may be both artificial and natural materials like casein milk protein, and cellulose derivatives, however, most of the binders are synthetic resins [2]. Due to their physical and chemical characteristics, plastics have become a major commodity worldwide and have several applications in commercial and industrial products. However, the use of plastics comes with many harmful environmental impacts related to their production and poor methods of waste treatment. Plastic pollution is a serious problem worldwide, the increased use of plastic products, shift to single-use plastics, and inappropriate disposal of plastic waste have led to excessive accumulation of plastic litter in the natural environment and global plastic production increased from 2 to 380 million metric tons between 1950 and 2015, representing a 190-fold increase [3]. Approximately 80% of the generated wastes were reported to accumulate in landfills or the natural environment and Plastic products can take 20 to 500 years to decompose, inadequate disposal after use makes it a serious environmental problem today (Yan *et al*., 2024). Polyethylene Terephthalate (PET), Polyvinyl Chloride (PVC), Polystyrene (PS). Polyethylene (PE) and Polypropylene (PP) Plastic waste, which is one of the major causes of pollution in landfills and oceans, has raised global concern, primarily due to the high rate of production, high durability, and the lack of use of current waste management techniques. Recycling methods are preferable to reduce the impact of plastic pollution to some extent. In most cases, recycling is used to minimize the impact of plastic pollution but the techniques are associated with different drawbacks, such as high cost and decrease in product quality being among the notable ones [4]. Despite the countless socio-economic benefit of plastics, the continuous production, use, and disposal of plastics significantly increase the waste problem that is affecting the human–environment relationship. It has been estimated that, since 1950, an amount of 6300 Mt of plastic waste has been generated. To date, most of such wastes have been disposed of in landfills; whether the current practices of disposal continue, it has been estimated that, by 2050, 12,000 Mt of plastic waste will enter landfills or the environment [5].

Plastic recycling involves the entire process from waste collection to reprocessing into valuable form, with mechanical or chemical recycling as the major method of recycling. Recycled plastic often has lower quality than new ones and it requires pretreatment steps of cleaning, careful sorting, and drying, which is time-consuming and requires additional cost leading to inadequate and ineffective recycling rates recycling efforts face numerous challenges, including the high cost of recycling Plastic waste. Using plastic waste as raw material for producing valuable products and materials has been proposed to enhance the economic viability of plastic recycling. Recent studies have moved beyond the usual use of plastic waste in bitumen, and food production to more advanced applications, such as the generation of gaseous and liquid fuels, as well as valuable chemicals [6]. Although plastic waste recycling can be very expensive, it can significantly reduce fossil fuel utilization, power consumption, and landfilling, it lowers the carbon footprints while contributing to the global economy. Emphasis has been made that reprocessing 1 ton of plastic can save up to approximately 130 million kilojoules of energy, The Life cycle assessment carried out shows that this is a huge step toward climate control [7].

Plastic valorisation refers to the process of converting plastic waste into valuable products. It is a crucial aspect of waste management that helps to reduce plastic waste, conserve resources, and cut down on carbon footprint. The conventional methods of plastic waste management, such as disposal in landfills and incineration, have been associated with severe ecological, economic, and social problems [8]. With continued population growth and increasing industrialization, the amount of plastic waste generated is bound to rise, and proper handling of this waste is a significant challenge. Hence, the concept of plastic valorisation has emerged as a viable alternative for managing plastic waste [9]. There have been significant recent advances in plastic valorisation that highlight the potential of this technique in managing plastic waste. One of the recent breakthroughs is chemical recycling, which converts plastic waste into chemical building blocks and fuels. Chemical recycling utilizes technologies such as pyrolysis, gasification, and depolymerization to break down plastic waste into its constituent molecules. The process produces a wide range of products, including fuels, chemicals, and new plastics.

Mechanical recycling is another recent advancement in plastic valorisation. This technique involves the use of physical processes to transform plastic waste into new products. It is a widely accepted method of recycling plastic and uses relatively low energy while reducing the reliance on raw materials, thereby making it an environment-friendly option [10]. The use of recycled materials in packaging, construction, and automotive industries has also increased significantly, further highlighting the potential of mechanical recycling.

Biodegradable plastics have gained attention as a potential solution to plastic waste reduction. They are designed to break down naturally in the environment and biodegrade in water and soil, without leaving any toxic residues. These biodegradable plastics are made from natural sources and are emerging as a viable alternative to conventional plastics. Efforts are ongoing to improve their durability, mechanical properties, and cost-effectiveness. The utilization of plastic waste as a raw material for products such as clothing, furniture, and other household accessories is gaining popularity. This method is also sustainable, as the waste is converted into non-waste products [11].

Over the past few years, significant progress has been made in the field of plastic valorisation. Innovations in recycling technologies, waste management systems, and environmental policies have contributed to the development of more sustainable and efficient processes for converting plastic waste into valuable products [12]. In this article, we have discussed the recent advances in plastic valorisation and their implications for waste management and environmental sustainability.

One of the most significant recent advances in plastic valorisation is the development of chemical recycling technologies. Chemical recycling involves breaking down plastic waste using chemical processes to produce valuable products such as fuels, waxes, and chemicals. This method offers significant advantages over traditional mechanical recycling, as it can handle a wider range of plastics and is not affected by contamination. Companies such as Agilyx and Plastic Energy have successfully implemented commercial-scale chemical recycling technologies, with plans for further expansion [13]. Collaborations between research institutions and industries have led to further innovations in chemical recycling, such as the development of new catalysts that involve low energy input and high efficiency. Another recent advance is the use of plastic waste as a feedstock for the production of bioplastics. Bioplastics are plastics that are made from renewable materials such as starch or cellulose. By using plastic waste as feedstock, the environmental impact of bioplastic production can be reduced. Bioplastics can be biodegradable, further reducing their environmental impact. Companies such as Carbios and Loop Industries are leading the way in developing bioplastics made from recycled plastics, with exciting prospects in the packaging and textile industries [14].

The development of waste-to-energy systems that convert plastic waste into energy is also a recent advance in plastic valorisation. Such systems involve the incineration of plastic waste to generate electricity or heat. While incineration has traditionally been viewed as a less environmentally friendly option compared to recycling, advancements in technology have improved its efficiency and reduced its emissions. Waste-to-energy systems are especially relevant in areas where waste management infrastructure is inadequate, as they can help reduce waste volume and generate energy. Companies such as Brightmark Energy are investing in waste-to-energy systems that have significant potential for reducing plastic waste and providing clean energy [15].

Plastic Waste Utilization

Plastic is one of the most commonly used materials in the world. It is lightweight, durable, and cheap. However, the widespread usage of plastic has created a major environmental problem: plastic waste. According to the World Economic Forum, the world produces about 300 million tons of plastic waste every year, and only about 14% of it is recycled [16]. The rest end up in landfills or as litter in the environment, where it takes hundreds of years to degrade, polluting our oceans and harming wildlife. However, with recent advances in technology and innovation, we can now transform plastic waste into new, useful products, reducing the need for virgin plastic and preventing plastic pollution.

There are several ways to utilise plastic waste. It can be recycled into new products, turned into fuel, transformed into building materials, or used as raw material for 3D printing. One of the most common uses of plastic waste is recycling. Plastic recycling involves collecting, sorting, washing, and processing plastic waste into new materials that can be used to make new products. The recycled plastic products include plastic bags, pipes, clothing, and even furniture. Recycling plastic not only prevents plastic waste from ending up in the environment, but it also conserves natural resources and reduces greenhouse gas emissions [17].

Another way to utilise plastic waste is through pyrolysis, a process that involves heating plastic waste to high temperatures in the absence of oxygen to produce fuel. The end products of pyrolysis include crude oil, gas, and carbon black. The crude oil can be further refined into diesel or gasoline, while the gas can be used to produce electricity. Pyrolysis is a promising technology that can turn plastic waste into a valuable resource while reducing our dependence on fossil fuels.

Transforming plastic waste into building materials is another innovative way to utilise it. For instance, a startup called ConceptosPlásticos in Colombia turns plastic waste into building blocks, which are used to construct houses and schools. The company collects waste plastic and melts it down into moulds. The resulting blocks are lightweight, fire-resistant, and easy to assemble [18]. This technique is not only an eco-friendly way of constructing buildings but also helps to reduce plastic waste.

3D printing is also a promising way to use plastic waste. A company called Precious Plastic has designed a machine that can transform plastic waste into filaments, which can be used for 3D printing. The filaments can be used to create various products, from phone cases to furniture. This approach provides a cost-effective way for designers and entrepreneurs to create innovative products while reducing plastic waste.

Recent advances in plastic waste utilisation have led to several successful implementations of plastic waste utilisation around the world. In India, a startup called EnviGreen has developed an alternative to plastic bags that is made from natural starch and vegetable oils. The resulting bags are 100% biodegradable and compostable, making them a sustainable alternative to plastic bags [19]. EnviGreen has also developed plates, straws, and utensils from the same material. This initiative has the potential to reduce plastic waste and help address India's plastic pollution problem.

In Kenya, a social enterprise called Lorna Rutto'sEcopost utilises plastic waste to create environmentally friendly fencing posts. Ecopost collects plastic waste, cleans and shreds it, and then mixes it with waste sawdust and non-biodegradable waste to create posts. The resulting product is durable, resistant to termites and water damage, and can last for up to 50 years. Ecopost has not only created an eco-friendly solution to post-fencing but also provided jobs to local communities and reduced plastic waste.

Utilising plastic waste is an essential step towards reducing plastic pollution and conserving natural resources. Recent advances in technology offer innovative ways to transform plastic waste into useful products and resources, from recycling to 3D printing. Examples of successful implementations of plastic waste utilisation show the potential of these innovations to create a sustainable future. However, more research and investment are needed to further advance plastic waste utilisation and promote a circular economy. As consumers, we can also support this cause by reducing our plastic consumption and properly disposing of plastic waste [20].

Plastic Waste Recycling

1. Mechanical Recycling

Mechanical recycling is a physical process of plastic waste conversion into reusable materials without affecting its chemical structure. Although this method divides fibers during the shredding process damaging some mechanical properties of the plastic waste. The process starts with collection and sorting. The collected pieces are ground, and the obtained flakes are further separated based on colour, resins, and other physical properties. Next, the chips are washed, melted, and homogenized into pellets. Mechanical recycling is limited by contamination, polymer degradation, and challenges in handling mixed or composite plastics [21].

Mechanical recycling alone cannot solve the plastic waste problem due to limitations such as the melting process used to produce granulate, which makes it only suitable for thermoplastic polymers, excluding neuroplastic polymers such as epoxides and polyurethane from the process. Furthermore, the polymers recycled must be clean to produce high-quality granulates that can effectively replace the primary resource [22].

Mechanical recycling is a process of recycling materials by shredding, grinding, and washing them to produce new products. This process is typically used for materials such as plastics, metals, and paper, and it involves the physical transformation of these materials into new products without any significant chemical changes. The process is relatively simple, but it requires advanced technologies and equipment to ensure that the recycled materials meet the required specifications for use in new products.

The mechanical recycling process typically starts with the collection of waste materials from various sources, such as households, businesses, and industries. The collected materials are then sorted and separated based on their type, quality, and other characteristics, to ensure that only suitable materials are recycled. The sorted materials are then sent to a recycling facility, where they undergo a series of processing steps to produce new products [23]. One critical step in mechanical recycling is shredding or grinding. This step involves reducing the size of the waste materials to make them easier to handle and process. The shredding or grinding process can also help to remove impurities such as paper labels, adhesives, or other contaminants that may affect the quality of the recycled material. After shredding or grinding, the materials are washed to remove any remaining contaminants or dirt, and the resulting clean material is finally converted into new products.

2. Recent breakthroughs in mechanical recycling technologies

Recent breakthroughs in mechanical recycling technologies have led to significant improvements in the efficiency and effectiveness of the process. For example, new technologies have been developed that can identify and separate different types of plastics based on their molecular characteristics, allowing for more accurate sorting and recycling. Some mechanical recycling plants also use specialized equipment, such as electrostatic separators and air classifiers, to remove non-plastic contaminants and produce clean, high-quality recycled plastic [24].

Another recent development in mechanical recycling is the use of advanced sensors and artificial intelligence (AI) to monitor and optimize the recycling process. For example, sensors can be used to detect the presence of contaminants in the recycled material and adjust processing parameters to ensure that the final product meets the required specifications. AI can also be used to analyze data from sensors and other sources to identify patterns and optimize the recycling process for maximum efficiency and effectiveness.

The successful implementation of mechanical recycling has been seen in many industries worldwide. For example, the automotive industry has embraced mechanical recycling to produce new car parts from recycled plastics and metal. The construction industry is also making use of mechanical recycling to produce asphalt and concrete from recycled materials such as rubble and crushed rock.

One example of a successful mechanical recycling project is the United States-based company Terra Cycle®.

TerraCycle® works with businesses and individuals to recycle hard-to-recycle materials such as cigarette butts, coffee capsules, and candy wrappers. The waste materials are shipped to the TerraCycle® recycling facility where they are sorted and processed using mechanical recycling techniques to produce new products such as plastic lumber, park benches, and other products [25].

Mechanical recycling is an essential process for reducing waste and producing new products from waste materials. Recent breakthroughs in mechanical recycling technologies have led to significant improvements in the efficiency and effectiveness of the process, as well as new opportunities for reusing waste materials. The successful implementation of mechanical recycling in industries such as automotive, construction, and waste management, highlights the potential for this process to contribute to a more sustainable and circular economy

3. Chemical Recycling

Chemical recycling involves reducing plastic polymers into new polymers or converting plastics to other chemical products. Recently, various chemical recycling processes have been in use for various types of plastics, these processes include pyrolysis, hydrocracking, and solvolysis Innovative chemical and hybrid processes have been developed to improve the quality and quantity of recycling throughput [26]. Catalysts are often used to increase energy efficiency and economic viability of chemical recycling, improve the sustainability and scalability of the process, and reduce the cost of thermal processes of pyrolysis and gasification for the production of petrochemical feedstocks such as naphtha, liquid, and waxy hydrocarbons and gases. This reduces the activation energy required for the depolymerization of plastic polymer waste, leading to lower reaction temperatures and shorter reaction times. Other chemical methods include hydrocracking and Solvolysis [27].

Chemical recycling is a process that involves the breakdown of plastic waste into chemical building blocks and fuels. The process utilizes various technologies such as pyrolysis, gasification, and depolymerization to convert plastic waste into its constituent molecules. These molecules can then be used to create brand-new products such as fuels, chemicals, and even new plastics. The process of chemical recycling usually starts with the collection and sorting of plastic waste. The waste is then pre-processed to remove any contaminants such as paper and dirt. The resulting clean plastic waste is then subjected to the chemical recycling process.

In the pyrolysis method, plastics are heated up to high temperatures in the absence of oxygen to produce a gas. The gas is condensed and collected to produce a liquid product that can then be used as fuel or feedstock in the chemical industry. Pyrolysis can take place in a batch or continuous process and is capable of converting a broad spectrum of plastics into useful products.

In gasification, the plastic waste is heated in the presence of oxygen or air to generate a synthetic gas. The synthetic gas can be used to generate heat and electricity or as feedstock in petrochemical processes. Gasification is a flexible technology that can handle various types of plastic waste and produce various by-products.

Depolymerization operates by breaking down the long polymer chains of plastic into smaller components. The plastic waste is treated with solvents or catalysts, which break down the polymer chains, resulting in compounds that can be used in different industrial applications [28]. Degradation can also occur through biological means when certain microorganisms feed on the plastic to break down the polymer chains.

4. Recent Breakthroughs in Chemical Recycling Technologies

There have been tremendous breakthroughs in chemical recycling technologies in recent years, presenting incredible new opportunities that were previously not available. One of the remarkable breakthroughs in chemical recycling is the use of microwave technology. This breakthrough involves exposing plastic waste to microwave radiation, causing it to heat up, break down, and release its constituent molecules. This makes it easier to separate the waste components, allowing them to be processed more efficiently and cost-effectively [29].

Another breakthrough in chemical recycling is the use of enzymatic depolymerization technology. This technology utilizes naturally occurring enzymes to break down plastic waste into its constituent molecules. As enzymes can be very specific in breaking down certain plastic polymers, this technology is highly selective and can produce high-quality building blocks for subsequent manufacturing processes. Researchers have also innovated a technique to convert plastic bags into useful products such as carbon nanotubes which can act as conductive filler materials that enhance the electrical properties of composite materials or as lightweight, high-strength reinforcing materials.

5. Successful Implementation of Chemical Recycling

Some cases of successful implementation of chemical recycling include the development of advanced recycling technologies like the UNCOL, which is a patented technology that converts mixed waste plastics to renewable hydrocarbon fuel. This technology is seen as promising, as it has the potential to not only recycle low-value mixed plastics but also produce value-added products. The technology has been implemented in several cities globally. Similarly, the SABIC chemical company achieved a significant breakthrough by using chemical recycling to convert low-quality mixed plastic waste into high-quality, uniform materials, suitable for a wide range of applications. The plastic was transformed into valuable monomers for use in the production of new materials that matched the quality of new plastics, offering a way of boosting recycling rates while reducing the environmental impact of plastic waste [30].

Another example is the use of Pyrowave's catalytic microwave depolymerization technology to convert post-consumer polystyrene containers into a recycled styrene monomer with chemical properties that are identical to virgin polystyrene. This technology is expected to scale to industrial-level operations and offer an economical solution for recycling polystyrene which is a common source of marine pollution. Chemical recycling has immense potential in dealing with plastic waste and represents an important opportunity to reduce the environmental impact of plastics. The recent advances in chemical recycling technologies present an exciting new frontier in managing plastic waste. With the ongoing development of new technologies for chemical recycling, we can expect to see increased implementation of the process worldwide which will help to preserve natural resources and prevent further damage to the environment.

6. Biodegradable plastics

Biodegradable plastics are a type of plastic that break down into natural components such as water, carbon dioxide, and biomass under specific environmental conditions. These materials are designed to decompose quickly, eliminating plastic waste that has become a significant environmental concern. Biodegradable plastics can be made from a variety of sources, including plant-based materials and petrochemicals. This article will provide a detailed explanation of biodegradable plastics, recent breakthroughs in biodegradable plastics research, and the advantages and limitations of this type of material.

Biodegradable plastics are classified into two main categories, i.e., biodegradable plastics and compostable plastics. Biodegradable plastics are those that break down spontaneously under specific environmental conditions, such as exposure to sunlight or soil microorganisms. Compostable plastics, on the other hand, are those that can be decomposed in an industrial compost facility where certain specific conditions of temperature, humidity, and microbial activity are met. Biodegradable plastics are the more easily available of the two types of materials [31].

One of the recent breakthroughs in biodegradable plastics research has been the development of new materials from agricultural waste such as rice husks, straw, and cassava. These materials are biodegradable and can be used in the production of packaging materials, bags, and other products. In addition, researchers have begun using enzymes to break down biodegradable plastics into their natural components more rapidly, making them more effective in reducing plastic waste [32].

7. Advantages of biodegradable plastics:

Environmental Benefits: Biodegradable plastics offer significant environmental benefits by reducing the amount of plastic waste that ends up in landfills and oceans. They break down rapidly under certain environmental conditions and leave behind no harmful residues.

Renewable Resource: Biodegradable plastics can be made from renewable resources such as corn, potatoes, and other plant materials, offering an eco-friendly alternative to petroleum-based plastics

Versatile Products: Biodegradable plastics can be used in a wide range of applications, including packaging, food and drink containers, and disposable items such as cups, plates, and utensils.

Reduced dependence on fossil fuels: Biodegradable plastics produced from plant-based sources require fewer fossil fuels, reducing the carbon footprint of the plastic industry.

8. limitations of biodegradable plastics:

Cost: Biodegradable plastics are often more expensive to produce than traditional plastics, making them less competitive in the market.

Limited Breakdown: Although biodegradable plastics break down more rapidly than traditional plastics, they require specific conditions to fully decompose. In addition, some types of biodegradable plastics can only be broken down in industrial composting facilities, limiting their ability to reduce plastic waste in the environment.

Lack of Standards: There are no established standards for biodegradable plastics, making it difficult for consumers and businesses to determine the effectiveness of different products.

Land Use Impacts: Biodegradable plastics made from plant-based sources can have environmental impacts, such as the use of large amounts of land for growing crops, which can lead to deforestation and other negative effects.

Biodegradable plastics have the potential to significantly reduce plastic waste and offer numerous environmental benefits. Recent breakthroughs in research have led to the development of new materials from agricultural waste that can be used to produce biodegradable packaging and other products [33]. However, biodegradable plastics also have limitations, including cost, limited breakdown, lack of standards, and land use impacts. Despite these limitations, biodegradable plastics remain a promising option for reducing plastic waste and creating a more sustainable future.

9. Biological Recycling

Biological recycling is used for biodegradable polymers. Biopolymers are recovered and degraded via the action of aerobic composting, fungi, and bacteria, as well as the action of other microorganisms [34]. Though synthetic polymers were mostly considered resistant to microbial degradation, more recent studies have shown that certain microbes have evolved to produce a variety of hydrolytic enzymes that allow them to degrade and process polymers. Biorecycling is successfully carried out through microbial and enzymatic degradation processes, followed by a chemical or biological conversion of the degraded monomers into polymers or other valuable chemicals [35].

10. Upcycling of plastic

Plastic upcycling is emerging as a promising alternative, as it uses abundant waste products as chemical feedstock to produce materials and essential chemicals of higher economic value. This method of valorisation reduces waste accumulation while creating economic opportunities by transforming discarded materials into higher-value products simultaneously, making it an effective solution to address the challenges posed by plastic waste. Upcycling plastic waste into carbon-based materials with diverse nanostructures and morphologies such as hierarchical porous carbon, carbon nanotubes, graphene, carbon quantum dots, and carbon-based composites offers significant use in various applications, including water treatment.

11. Drawback of Plastic WasteRecycling

The drawback of plastic recycling strongly depends on the variety of plastic types. Waste collection does not end up in the separation of the different plastic types. Hence, problems associated with compatibility have to be resolved before the recycling process commences. Where collection takes place, there are different plastic families and grades within the same family, therefore their separation has to be carried out to sort out various materials. The introduction of one polymer into another such as in the production of multilayer films, often leads to a reduction in the properties of the recycled material [36]. This observation comes from the fact that each polymeric material has properties specific to it and processing features that may not be compatible with the ones of other materials. For example, thermal properties can influence the compatibility between different polymers this means that the temperature required for proper processing of a certain material is too high for another one which will eventually degrade and yield an unusable recycled material. On the other hand, if such a temperature is too low to allow the melting of some polymeric fractions, the latter will be present as an unmelted solid particle in the molten matrix, leading to defects and loss of mechanical properties [37].

Methods of Sorting for Plastic Valorization

1. Physical Sorting

This type of sorting consists of a manual sorting technique of material involves identification by shape, colour, appearance, and trademark, it involves hand-picking plastics based on visual identification, which is simple but labour-intensive. Mechanical sorting is another form of physical sorting that uses automated systems, including size-based separation with screens or sieves and shape sorting using ballistic separators. It generally involves centrifugal force, specific gravity, elasticity, particle shape, selective shredding, and mechanical properties to separate the mixture of plastics [38]. Also, Density-based methods like sink-float separation use water to differentiate plastics based on high density (that sink) from low density (those that float), while air sorting classifies based on specific gravity by feeding the plastic into air causing lighter particles to be separated from heavier ones [39].

2. Optical Sorting Methods

These sorting methods are automated facilities consisting of various methods that use light-based technologies to identify and sort plastics with high speed of identification and precision, such as Near-Infrared (NIR) spectroscopy detects polymers by analyzing their spectral signatures, although this method is not suitable for identification of dark coloured plastics, while visual cameras are used to sort plastics based on colour differences [40].

3. Electromagnetic and Electric-Based Sorting

These are electric-based sorting methods, they utilize the magnetic or electrical properties of materials to achieve separation. Magnetic separation is often used to remove ferrous metals from plastic waste, while eddy current separation depends on magnetic fields to remove non-ferrous metals. Electrostatic sorting separates the plastic materials through their differences in electrostatic charges. The materials are sorted by letting them fall freely through an electric field produced between two parallel sets of oppositely charged electrodes and are separately collected according to the triboelectric charge that they have [41].

4. Analytical and Chemical Sorting Methods

Analytical and chemical sorting methods use chemical composition, thermal behaviour, and molecular structure to identify plastics. In the chemical process, the polymer molecules are converted back to raw monomers in other to be reused in the manufacture of new polymer. Analytical methods like spectroscopic methods, thermal analysis, Chromatographic techniques, and X-ray-based methods are used to obtain chemical data from plastic in a non-destructive manner [42].

Challenges in Plastic Waste Valorisation

Challenges in plastic waste Plastic valorisation refers to the process of converting plastic waste into valuable products. It is one of the most effective ways to address the issue of plastic pollution, as it not only reduces the amount of plastic waste but also helps to conserve natural resources and reduce greenhouse gas emissions. However, plastic valorisation faces several challenges that need to be addressed to develop a more efficient and sustainable process. In this article, we will discuss the challenges involved in plastic valorisation and possible solutions to overcome them [43].

One of the major challenges in plastic valorisation is the lack of efficient recycling methods. While plastic recycling is a commonly used method to valorise plastic waste, it is not always effective. Obtaining high-quality recycled plastic requires careful sorting and processing to remove contaminants and preserve the quality of the material. This makes recycling a time-consuming and expensive process. Furthermore, some types of plastic are more difficult to recycle than others, such as multi-layered plastic or plastic that has been contaminated with organic materials like food residue or oil [44].

To overcome this challenge, innovative recycling methods that are more efficient and less costly are required. One solution that is gaining popularity is chemical recycling. Chemical recycling involves breaking down plastic waste using chemical processes to produce valuable products such as fuels, waxes, and chemicals. This method offers significant advantages over traditional mechanical recycling, as it can handle a wider range of plastics and is not affected by contamination. Another solution is to develop more efficient sorting technologies that can separate different types of plastics, making it easier to recycle them effectively.

Another challenge in plastic valorisation is the availability of raw materials. While plastic waste is abundant, it is not always easy to collect and process it. Plastic waste is often scattered and hard to collect, and some types of plastic are more frequently discarded than others [45]. The logistics of transporting and processing waste can be challenging, especially in areas with an underdeveloped waste management infrastructure.

To address this challenge, effective waste management systems must be established to ensure that plastic waste is collected and properly disposed of. This can be achieved by encouraging communities to recycle and implementing policies that incentivize businesses to reduce their use of plastic packaging. Additionally, investment in recycling infrastructure can lead to more effective collection and processing of plastic waste. One example of such infrastructure is the development of waste-to-energy plants that convert plastic waste into energy [46].

A third challenge in plastic valorisation is the limited demand for recycled plastic products. While there is an increasing demand for sustainable products, the market for recycled plastic is still small. This is partly due to the perception that recycled plastic is of lower quality than virgin plastic, which can limit its use in high-value products. Additionally, many companies are still not incentivized to use recycled plastic due to the higher cost of production compared to virgin plastic [47].

To address this challenge, initiatives must be undertaken to increase demand for recycled plastic products. This can be achieved by educating consumers about the benefits of recycled plastic and promoting the use of recycled plastic products through marketing campaigns [48]. Policies that incentivize companies to use recycled plastic can help to create a more significant demand for recycled plastic. One example is a deposit scheme for plastic bottles that encourages consumers to return their bottles for recycling, thereby increasing the availability of recycled plastic.

A final challenge in plastic valorisation is the environmental impact of the process. While plastic valorisation can reduce plastic waste and conserve natural resources, the process itself can also contribute to greenhouse gas emissions and other environmental impacts. For example, some plastic valorisation processes require high energy input or emit toxic gases. Additionally, the production of some plastic valorisation products may require further processing or disposal, contributing to the overall environmental impact of the process [49].

To address this challenge, it is essential to develop more sustainable and environmentally friendly plastic valorisation processes. This can be achieved by investing in renewable energy sources and developing cleaner chemical processes [50]. The development of eco-friendly products that can be made from plastic waste, such as biodegradable plastics or building materials, can help to reduce the environmental impact of the process.

Plastic valorisation presents a promising solution to the problem of plastic pollution, but it also faces several challenges. To develop a more efficient and sustainable process, innovative recycling methods, effective waste management systems, increased demand for recycled plastic products, and environmentally friendly processes are required. By addressing these challenges, plastic valorisation can help reduce plastic pollution, conserve natural resources, and create a more sustainable future.

Conclusion

Plastic valorisation is playing an increasingly significant role in waste management and environmental sustainability. With an increasing awareness of the harmful effects of plastic pollution on the environment, there is a growing demand for sustainable solutions. Initiatives such as the European Union's Circular Economy Action Plan and the United Nations Sustainable Development Goals focus on reducing waste generation, increasing recycling rates, and promoting sustainable production and consumption. Plastic valorisation is an essential tool in achieving these goals, as it not only helps to reduce plastic waste but also contributes to a more circular economy.

There are several implications of plastic valorisation on waste management and environmental sustainability. Plastic valorisation can contribute to reducing waste generation and increasing recycling rates, leading to a more sustainable waste management system. Plastic valorisation can help conserve natural resources and reduce greenhouse gas emissions by replacing virgin materials and fossil fuels. Plastic valorisation can create new economic opportunities and jobs in the recycling and manufacturing industries. However, it is essential to ensure that plastic valorisation processes are environmentally friendly and do not contribute to further pollution or resource depletion. This requires careful consideration of the entire life cycle of plastic valorisation products, from raw material extraction to disposal.

Plastic valorisation presents a promising solution to the problem of plastic pollution. Recent advances in recycling technologies, waste management systems, and environmental policies have contributed to the development of more sustainable and efficient processes. Looking into the future, decentralized recycling systems and the development of bioplastics and waste-to-energy systems hold significant promise for reducing plastic waste and contributing to a more circular economy. While there are challenges and implications to be addressed, plastic valorisation presents an opportunity for a more sustainable and prosperous future.

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