

Review

Advancements in PET Packaging: Driving Sustainable Solutions for Today's Consumer Demands

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Abstract: This work provides an overview of the importance of recycling PET waste to reduce the environmental impact of plastic waste, conserve natural resources and energy, and create jobs in the recycling industry. Many countries have implemented regulations and initiatives to promote the recycling of PET waste and reduce plastic pollution, such as extended producer responsibility (EPR) systems, bans on certain single-use plastics, and deposit–return systems for plastic bottles. The article further underscores the versatility of recycled PET, as it can be transformed into various products such as fibers, sheets, film, and strapping. These recycled materials find applications in numerous sectors including clothing, carpets, upholstery, and industrial fibers. Recognizing the importance of collaboration among governments, industries, and individuals, we emphasize the need for sustainable PET waste management practices and the promotion of recycled materials. The article also provides information on India's experiences with PET waste management and regulations in other countries. It is important to note that the global production and consumption of PET have increased significantly in recent years, with the packaging industry being the largest consumer of PET. This has resulted in a significant increase in the generation of PET waste, which poses a significant environmental and health hazard if not managed properly. PET waste can end up in landfills, where it can take hundreds of years to decompose, or it can end up in the oceans, where it can harm marine life and the environment. Therefore, the proper management and recycling of PET waste are essential to mitigate these negative impacts. In terms of India's experiences with PET waste management, several initiatives have been implemented to promote the recycling of PET waste. For example, the government has launched the Swachh Bharat Abhiyan campaign, which aims to promote cleanliness and sanitation in the country to promote waste segregation and recycling.

Keywords: polyethylene terephthalate (PET); PET waste; waste management; recycling PET; legal status



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1. Introduction

Polyethylene terephthalate (PET) is a widely used thermoplastic with excellent properties, making it a popular choice for various packaging and single-use plastic products. Its exceptional tensile strength, processability, transparency, thermal stability, barrier properties, toughness-to-weight ratio, and chemical resistance have contributed to its widespread

use [1]. However, the significant consumption of PET has led to a substantial amount of PET waste, especially in the form of single-use packaging. This has raised concerns about the environmental impact of plastic waste, such as marine pollution and landfill accumulation.

To address these concerns, there is a growing global movement to reduce single-use plastics and increase PET recycling efforts. Various strategies have been proposed, including promoting reusable products, exploring sustainable packaging options like bioplastics, implementing deposit–return systems for plastic bottles and other packaging, and investing in recycling programs and infrastructure. These efforts aim to minimize plastic consumption, increase recycling rates, and encourage the adoption of sustainable materials in the packaging industry.

Sustainable packaging solutions have gained momentum in recent years due to consumer awareness and environmental considerations. PET has emerged as a leading candidate in the pursuit of eco-friendly packaging materials due to its recyclability and potential for a circular economy. The ability to collect, process, and transform used PET products into new packaging materials offers a significant opportunity to reduce reliance on virgin resources and minimize waste. PET's transparency also plays a crucial role, allowing vibrant colors and product visibility, enhancing brand recognition, and engaging consumers. Furthermore, PET's exceptional barrier properties protect sensitive contents, extending product freshness and shelf life.

As consumer lifestyles evolve, PET packaging continues to meet the demands for convenience and on-the-go products. Its lightweight nature reduces material waste and provides portability and ease of use for single-serve applications.

This paper aims to discuss effective handling and management techniques for PET packaging waste, focusing on best practices for the collection, sorting, and recycling processes. The objective is to optimize resource utilization and minimize environmental impacts throughout the lifecycle of PET packaging [2–4].

By promoting responsible waste management and environmental stewardship, we seek to inspire individuals, businesses, and policymakers to embrace sustainable packaging solutions. Through education and advocacy, we aim to drive positive change and foster collective efforts in reducing the environmental impact of PET packaging.

Overall, this paper addresses the pressing need for sustainable PET packaging practices, emphasizing the importance of proper waste management and the adoption of environmentally friendly alternatives. By raising awareness and providing guidance, we strive to contribute to a greener and more sustainable future in the packaging industry.

On the other hand, because of its growing consumption and non-biodegradability [5], its waste has increased over the years and poses a severe environmental hazard when discarded after use. PET waste contributes 12% by volume of the world's solid waste, with its volume increasing at an alarming rate [6,7]. PET waste discarding began to pose severe economic and environmental issues with the upsurge in its amount. Economic, environmental, and energy concerns emphasize the large-scale recycling of PET. PET recycling does not only serve as a partial solution to the substantial PET waste problem, but also subsidizes the energy conservation and raw products of the petrochemical industry [8]. The production and consumption of plastic/packaging/PET materials are directly associated with the generation of plastic/packaging/PET waste.

The primary aim of this review article is to explore strategies for reducing and eliminating plastic, packaging, and PET waste through various environmental recycling methods. The objective is to lessen the burden on landfills and mitigate the environmental impact of these materials.

In summary, this paper focuses on several objectives related to PET packaging. Firstly, it highlights the importance of PET as a widely used thermoplastic with excellent properties. Secondly, it discusses effective waste management techniques to address the environmental concerns stemming from PET waste, especially single-use packaging. Thirdly, the paper addresses the challenges and opportunities related to PET packaging, exploring innovative solutions that support a more circular economy and reduce reliance on traditional PET

materials. Furthermore, the paper aims to promote responsible practices in the packaging industry, encouraging the adoption of sustainable alternatives and recycling efforts. By achieving these objectives, the ultimate goal is to contribute to a more sustainable and environmentally conscious approach to PET packaging

2. Production and Consumption of PET

2.1. PET Production

The global polyethylene terephthalate (PET) market is expected to witness significant growth in the coming years. According to market forecasts, the market is estimated to surpass USD 72.88 billion by the end of 2030 in terms of revenue, exhibiting a compound annual growth rate (CAGR) of 6.7% during the forecast period from 2022 to 2030 [9]. PET, which is produced in various forms such as films, bottles, fibers, and resin, is widely recognized as an economically viable option in the packaging industry, particularly for beverages. PET bottles and PET fibers continue to dominate the market, accounting for 30.3% and 63.5% of the total global PET production, respectively, while polyester film and resin account for 6.2 shown in Figure 1 [10–12]. The market's steady growth can be attributed to factors such as increased demand for sustainable packaging solutions, growth in the beverage industry, and the versatile applications of PET in various sectors. As the market progresses, it will be crucial for industry stakeholders to monitor emerging trends and invest in innovative technologies to meet the growing demand for PET products. The size of the global polyethylene terephthalate (PET) resin market was estimated at USD 80.9 million in 2021, and is anticipated to increase from USD 85.11 million in 2022 to USD 127.67 million by 2030, expanding at a CAGR of 5.2% during the forecast period (2023–2030) [13].

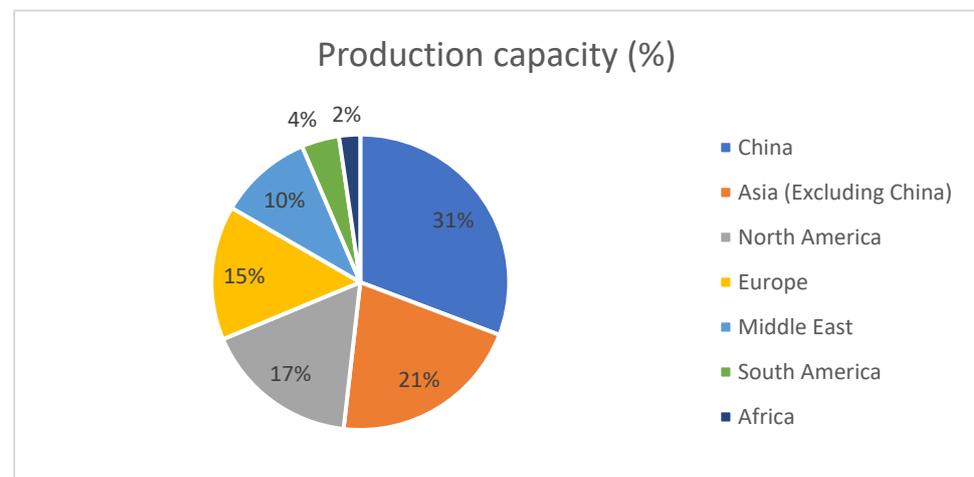


Figure 1. Worldwide PET resin production capacity [11].

2.2. PET Consumption Market

The Middle East is currently experiencing rapid growth in various industries, making it the fastest-growing market globally, with a Compound Annual Growth Rate (CAGR) of 7.15% in terms of value. This growth is primarily driven by two key factors: the increasing manufacturing output of electrical and electronics products, and the rising demand for food and beverage packaging. Saudi Arabia and the United Arab Emirates are projected to remain the largest consumers in the region, with consumption volumes reaching around 47% and 41%, respectively, by 2029. These countries have established themselves as major players in the Middle East market, driven by their economic development and industrial expansion. The growing manufacturing output of electrical and electronics products in the Middle East is contributing to the demand for PET resin. This can be attributed to the region's focus on diversifying its economy and reducing dependence on oil revenue. The production of consumer electronics, such as smartphones, tablets, and

other electronic devices, has been increasing steadily, resulting in a higher demand for PET resin in electrical encapsulation and device manufacturing. The rising demand for food and beverage packaging is fueling the growth of the PET resin market in the Middle East. The region's expanding population, along with changing lifestyles and an increasing preference for convenience-sized products, has led to a surge in demand for PET-based packaging materials. PET offers excellent properties for packaging applications, including its lightweight nature, transparency, and ability to preserve the quality and freshness of packaged products. Overall, the Middle East market's robust growth in the electrical and electronics industry, as well as the food and beverage packaging sector, is driving the increasing consumption of PET resin. Saudi Arabia and the United Arab Emirates are expected to remain key players in the region, driving the market forward with their significant consumption volumes as shown in Figure 2 [14].

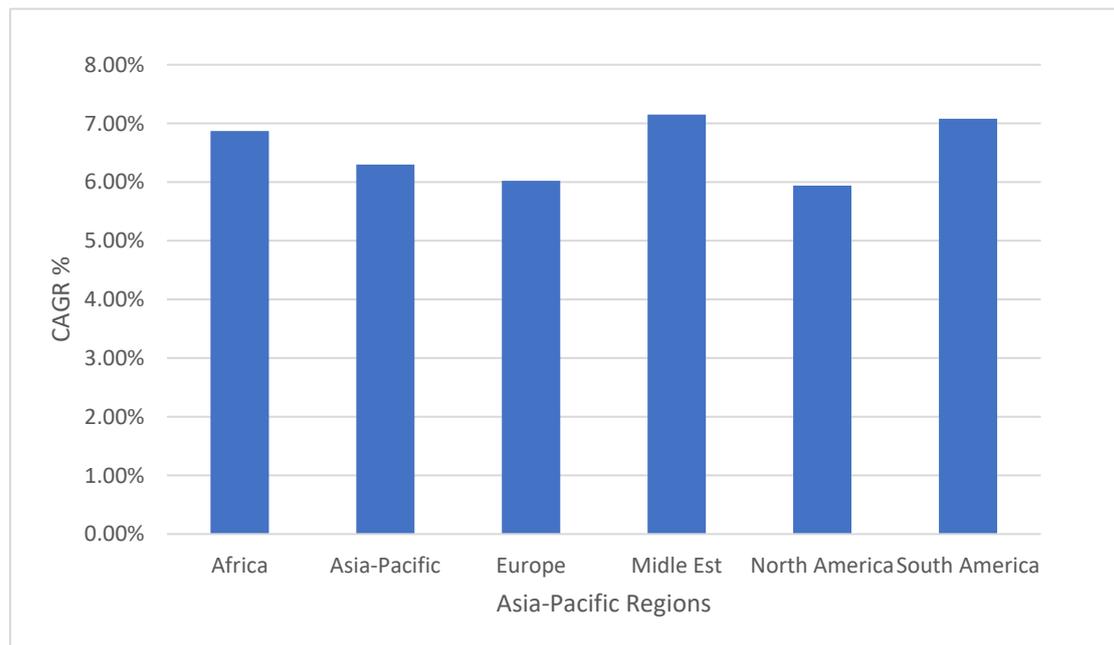


Figure 2. Polyethylene terephthalate (PET) market, CAGR, %, by region, 2023–2029 [14].

PET (polyethylene terephthalate) has a wide range of applications in various industries, including packaging, electrical, and electronics. It is commonly used for packaging foods and beverages, particularly in convenience-sized soft drinks, water bottles, and other packaging forms. Additionally, PET is utilized in electrical encapsulation, electrical devices, solenoids, and smart meters. The packaging sector accounts for a significant portion of the overall PET resin market's revenue, with approximately 96% in 2022. The global packaging industry is the largest end-user industry for PET resin. Factors such as a rising population, increasing income levels, and changing lifestyles contribute to the growth of the global plastic packaging industry. This, in turn, drives the demand for PET resin, especially in end-user segments such as FMCG (fast-moving consumer goods), food and beverages, pharmaceuticals, and others. The production of plastic packaging is expected to increase from 140 million tons in 2023 to around 180 million tons in 2029, reflecting the rising demand in the packaging industry. The electrical and electronics industry is the fastest-growing industry in terms of revenue, projected to register a Compound Annual Growth Rate (CAGR) of 7.88% during the forecast period of 2023–2029. This growth is primarily driven by the expanding consumer electronics market, which is expected to reach a value of USD 1103 billion in 2023. The factors contributing to this growth include the demand for lightweight products, the growth of e-commerce, a focus on sustainability, and higher adoption rates among major consumer product manufacturers. Furthermore, the revenue from electrical and electronics production is anticipated to achieve a CAGR of 6.71% during

the same forecast period. Consequently, the demand for PET resin in the global market is expected to witness significant growth in the near future [15].

3. Scenario of PET and Plastic Waste and Its Recycling

3.1. Global Scenario

Rapid urbanization and increased demand for PET materials, such as plastic packaging, have led to a significant increase in the production and consumption of these materials. This, in turn, has contributed to a rise in the amount of municipal solid waste (MSW) generation. Single-use plastic packaging, which is designed for immediate disposal, is a major contributor to this problem. According to Figure 3 [16], almost 97% of plastic wrapping is thrown away after a single use. India aims to entirely remove single-use plastic by 2022. It is estimated that in 2015, around 158 million tons of plastic material were discarded globally after a single use. This includes plastic packaging, disposable plastic products, and other single-use items. This amount is projected to increase in the coming years due to population growth, urbanization, and increasing consumption. It is important to note that this number is an estimation and might have some variation. Peru has banned the use of single-use plastics in its 76 protected cultural and natural areas, including popular tourist destinations like Machu Picchu, Manu, and Huascarán, as well as in national museums. This move aims to reduce the amount of solid waste generated in these areas, as tourists are a major source of plastic waste, particularly single-use wrapping and PET bottles. At Machu Picchu alone, invitees generate an average of 14 tons of solid waste per day. Plastic packaging accounted for around 50% of the plastic waste generated worldwide in 2015.

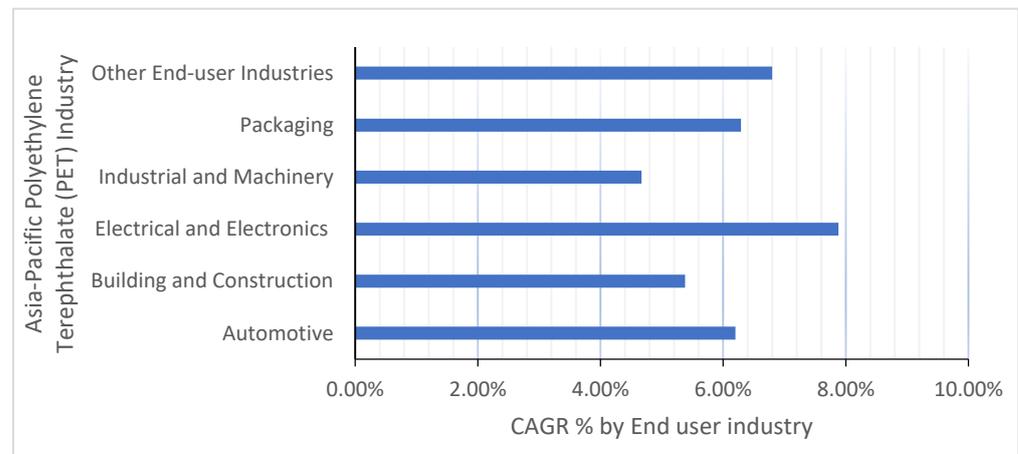


Figure 3. Polyethelene terephthalate (PET) market, CAGR, %, by end user industry, 2023–2029 [16].

In March 2019, the European Union voted to ban the top 10 single-use plastic items found on European beaches by 2021, so as to reduce plastic pollution on beaches and in the ocean. The EU also set a target of 90% of plastic bottles to be recycled by 2025 [17]. Member states were directed to work out the details of the ban before the 2021 deadline. Plastic packaging is a major contributor to coastal litter, accounting for 61% of litter found on worldwide coastlines, at around 300 million tons [18]. In 2015, plastic packaging waste accounted for 47% of the plastic waste generated worldwide. Half of this plastic packaging waste came from Asia, with China being the largest generator of plastic packaging waste worldwide shown in Figure 4. The United States was the largest generator of plastic packaging waste per capita, followed by Japan and the European Union. It is important to note that this information is based on a study from 2015, and the numbers might have changed since then. The Figure 5 depicts the plastic packaging waste generation in 2014, represented in million metric tons (MMt), and the corresponding per capita amount in kilograms (kg) [19].

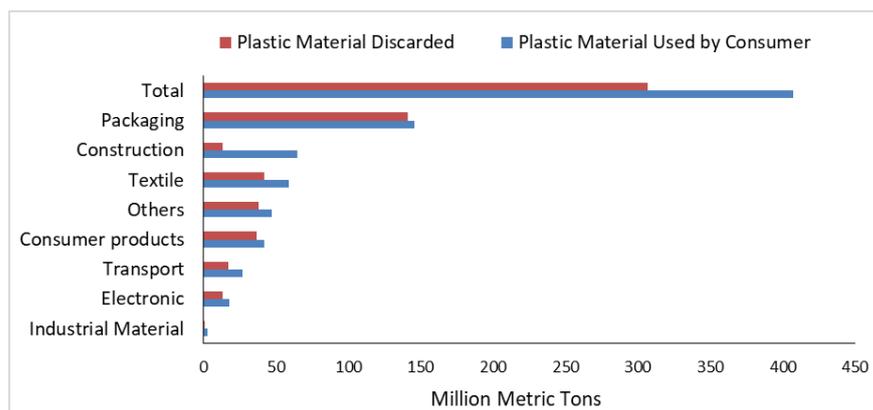


Figure 4. The global plastic material discarded after single use in the year 2015 [19].

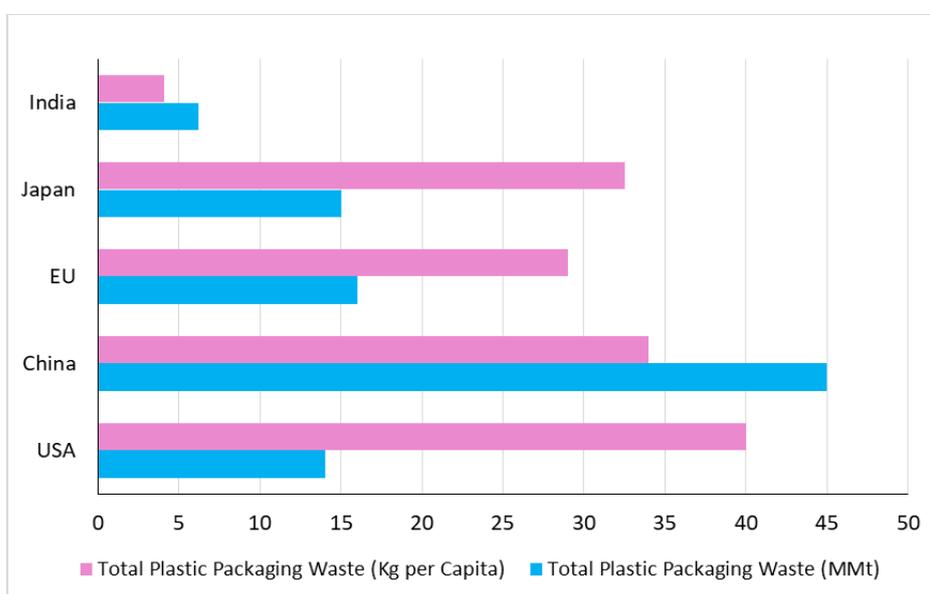


Figure 5. Plastic packaging waste generation in 2014 (MMt) [19].

Plastic products, including those of PET, are often dumped after use and generally form part of MSW. MSW is often a rich source of numerous kinds of recyclable materials such as plastic, paper, glass, and metal. This practice is still in vogue across continents such as the EU, Australia, the USA, India, etc. The general composition of MSW generated in the USA in 2013 is presented in Table 1 [20], which indicates that plastic waste, including PET waste, comprises about 13% of the MSW. Data from a report published by the EPA [21] show that plastic containers and packaging discarding are the primary sources of PET waste in MSW in the USA. Figure 6 shows the MSW generated from some prominent countries [22].

Table 1. Composition of MSW generated in the USA in 2013 [20].

Material in MSW	% of MSW Generated in 2013
Paper	27
Food	15
Yard trimming	13
Plastics	13
Metals	9
Rubber, leather and textiles	9
Wood	6
Glass	5
Other	3

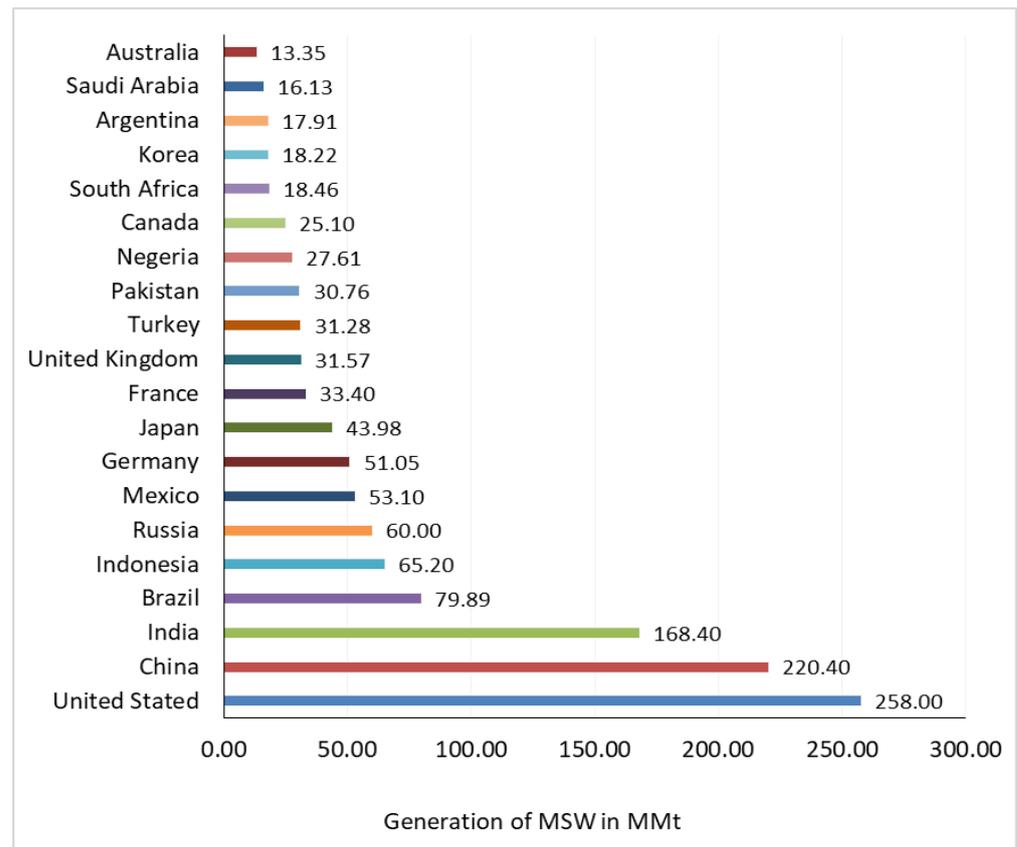


Figure 6. MSW generation in some prominent countries in 2017 [22].

3.2. Indian Scenario

The same as in the USA, PET also forms a significant fraction of the plastic waste in MSW in India [22]. Table 2 shows the average plastic waste generated in some of the metropolitan cities in India [23,24].

Table 2. Plastic waste generated (tons per day) in four metropolitan cities in India [24].

Metropolitan Cities in India	Plastic Waste Generated (Tons per Day)	Population (2011) (Millions)	GDP per Capita 2013 (\$)
Delhi	690	11.0	3580
Chennai	429	4.7	1860
Kolkota	426	4.5	1110
Mumbai	408	12.4	1990
Bengaluru	314	8.4	1430

A survey conducted in 60 major cities of India in 2012 [25] revealed that the daily generation of plastic waste in the country was about 15.3 kilotons, or 5.6 million tons, per year. While 60% of the plastic waste was collected and recycled, the remaining 40% went uncollected. This information is from a survey conducted in 2012, and the numbers might have varied since then. Normally, the cities with higher populations and higher GDP per capita create more waste (including plastic). Here, we look at Delhi and Mumbai, with almost the same population, but almost double the amount of waste was created in Delhi. The populations of Chennai and Kolkota are almost one-third that of Mumbai, but they created the same quantity of plastic waste because of the poor management of waste recycling. Several states in India have implemented bans on single-use plastics and have seen positive results. For example, in Maharashtra, a state in India, there was a reported

40% decrease in plastic waste in the seven months following the implementation of the ban. This indicates that the ban has been effective in reducing plastic waste in the area. However, it is important to note that this information is based on a specific case, and the results may vary in other regions or with different types of bans [26].

3.3. Worldwide Recycling Efforts

According to new research, after China's "Green Fence" action plan banned plastic waste imports in 2018, a significant portion of plastic waste exported from the US for recycling was shipped to other countries in Southeast Asia, such as Thailand, Malaysia, and Vietnam. In the first six months of 2018, around half of the plastic waste exported from the US for recycling was sent to these three countries. This indicates that the ban in China caused a shift in the destinations of plastic waste exported from the US. However, it is important to note that this information is based on a specific period, and the current situation may be different [27]. The previous year, the US exported more than 70% of its plastic waste to China and Hong Kong.

The recycling of PET waste is being adopted on a large scale in many countries across the globe to protect the environment and maintain sustainability [28]. Asia's largest PET bottle recycling factory, INCOM Resources Recovery, with an annual recycling capacity of 50 kt, is located in Beijing, China. The used PET plastic bottles are converted into clean PET plastic material for making new bottles through mechanical recycling. The recycling rate of PET bottles in China is reported to be almost 90% [29].

Japan is also involved in recycling waste plastics, where around 77% of plastic waste was recycled in 2010, up from 39% in 1996 and 73% in 2006 [30]. In 2010, Japan recycled 72% of PET bottles, compared with 48% in the EU and 39% in the UK. Further, in 2013, 0.47 million tons of post-use PET bottles were broken down through mechanical recycling. The recycled material was used for sheeting, textiles, industrial materials, and household products such as egg boxes. Further, enormous amounts of rPET are transported to Hong Kong, China, and some other parts of Asia, where it is used for making toys and games.

In collaboration with Alkem Nigeria Limited, a fiber processing manufacturer, Coca-Cola USA started a buyback and recycling scheme for used PET bottles in Nigeria. The joint venture-initiated Nigeria's first bottles-to-fiber recycling plant in 2005, and from 2005 to 2012 the total volume of bottles recycled increased from 135 tons to 6200 tons. This initiative not only helped to reduce plastic waste but also created jobs for an estimated 1500 people. In 2015, the Coca-Cola Company updated its PET bottling plant and created a 100% bio-PET version, aiming to switch entirely to bio-based plastics by 2020 [31].

More and more PET recycling plants are being set up in several countries due to the increase in PET waste. According to a study by the National Association for PET Container Resources (NAPCOR), an initiative was taken up in January 2013 to add four more PET recycling plants in the United States, with an additional capacity of 200 million pounds [32]. Similarly, a state-of-the-art PET recycling plant was built in England in 2012 with an operational capacity of over 50% of the UK's PET waste, and it has been reported to have sorted over 250 million plastic bottles since opening [33]. The plastic/PET waste, co-mingled with MSW, is first sorted by type (metals and plastics), and then further sorted by plastic properties, color, and quality, before subjecting them all to reprocessing.

3.4. Recycling Efforts in India

Recycling PET waste started in India in 1994, but the industry grew slowly. The mostly mechanical recycling process is being adopted to produce rPET fibers. As of 2014, about 25 industries were involved in PET waste recycling. Currently, M/s Ganesh Ecosphere (Shri Shyam Sunder Sharmma founder of the company) is reported to be the largest recycler of PET waste, with an annual capacity of 57,600 tons. M/s Crystic Resins India Pvt. Ltd., Reliance Industries, M/s Dhansari, and M/s JBT are the other major industries involved in this field. Bisleri, one of India's largest packaged mineral water industries, has also started recycling PET bottles [34]. The initiative involves the collection of PET bottles, crushing

them into fine flakes, and then using the same for the manufacture of fibers. The rPET fibers are being widely used for the production of carpets, t-shirts, handbags, window blinds, and other useful products. As already mentioned in Section 5.1 second para reverse vending machines are also being installed in different cities to collect and process used PET bottles.

Sustainable packaging is a growing concern for plastic manufacturers and fast-moving consumer goods (FMCG) companies. Companies like Unilever, one of the world's largest FMCG companies, are taking steps to address this issue. Unilever announced plans to make all its packaging "reusable, recyclable or compostable" by 2025. This goal is a part of Unilever's efforts to reduce its environmental footprint and promote sustainable packaging. Such steps taken by companies are expected to drive the development and adoption of more sustainable packaging solutions in the future.

Western India is the hub of the plastic recycling machinery market, its share being about 46%, followed by North India at 28%, South India at 22%, and East India at only 4%. Gujarat in Western India hosts a significant cluster of plastic recycling machinery manufacturers/suppliers as mentioned in Table 3 [35].

Table 3. Summary of where in India has introduced regulations on plastic/packaging products state-wise [35].

Sr. No.	Name of States	Impact	Year	Importance
1.	Local—New Delhi	Limited because of weak enforcement.	2017	Ban entirely all types of single-use plastics in New Delhi [36].
2.	Local—Himachal Pradesh	Significant decrease in plastic pollution.	2014	The Indian state of Himachal Pradesh has banned the production, storage, sale, use, and distribution of non-biodegradable plastic bags that are less than 70 microns in thickness under the Himachal Pradesh Non-Biodegradable Garbage (Control) Act, 1995. In 2011, the state also introduced a ban on disposable plastic products such as plastic cups, drinking glasses, and plates [37].
3.	Local—Punjab	Information not available.	2016	The state of Punjab in India has implemented a ban on the manufacture, stocking, distribution, sale, or use of single-use containers and plastic carry bags under the Punjab Plastic Carry Bags (Manufacture, Usage, and Disposal) Control. [38].
4.	Haryana	Limited because of weak enforcement.	2010	The state of Haryana in India has also implemented a ban on the manufacture, stocking, distribution, sale, or use of plastic carry bags [39].
5.	Local—Maharashtra	Information not available.	2018	The state of Maharashtra in India has placed a ban on plastic bags less than 50 microns [36].
6.	Local—Karnataka	Plastic bags stay to be both available and commonly used.	2016	The state of Karnataka in India banned manufacturing and sale of plastic bags.
7.	Local—West Bengal	Plastic bags are still commonly used. Implementation is limited.	2001	The state of West Bengal in India banned plastic bags of less than 40 microns and has enforced a blanket ban.
8.	Local—Kerala	Information not available.	2016	The state of Kerala has placed a ban on plastic bags less than 50 microns.
9.	Local—Sikkim	While plastic bags are still typical, majority switched to paper bags or newspapers (66%).	1998	The state of Sikkim in India has placed a ban on purchasing of goods and materials in plastic covers or plastic bags.

4. Unsustainable Disposal Methods of PET/Plastic Waste in Practice

Large quantities of MSW (containing PET and plastic waste) are still being disposed of through unsustainable methods, causing severe environmental damage. These methods are discussed below.

4.1. Disposal in Landfill

Plastic waste dumping in landfills, along with MSW, is a widely adopted practice, despite knowing that it leads to the wastage of valuable land resources, and with the awareness that is not considered a sustainable waste management practice. Besides occupying a vast area of land, it also generates odors and aerosols, causes visual disruption, and releases harmful chemicals and gasses through escape as leachates from landfills. Although the relative proportion of land occupied by plastic/PET waste is low in comparison to that of MSW, the damage caused to the environment by the same is enormous due to its non-biodegradable characteristics. Plastics/PET decompose very slowly and inhibit the breakdown of useful biodegradable materials from the soil. Despite this, the continued practice of dumping in landfills may be due to a lack of sufficient funds, and technical know-how, required to implement sustainable methods.

The average proportion of MSW dumped in landfills in the European Union is about 38%. Some of the leading European countries have stopped landfilling, or only a small proportion (up to 19%) is dumped into landfills, while the rest is diverted for recycling/compositing, or for waste-to-energy generation [40]. Australia also continues to depend on landfills to dispose of municipal solid wastes. Tata Energy Research Institute (TERI), India, estimated that about 1400 sq. Km of land area (equivalent to the city of Delhi, India) would be required by 2047 for dumping municipal waste in India [41].

The landfill deposition of MSW is more prevalent in the USA, where about 68% of MSW is dumped in landfills. This is attributed to opposition by environmental groups to adopting waste-to-energy processes. However, a large number of landfills (560 out of 1900) are implementing technologies to capture landfill gas (methane) and produce electricity, which is recognized as a renewable energy source. Although it is a welcome step, only about a third of the potent greenhouse gas is converted into electricity in reality.

4.2. Burning in an Open Environment

Burning PET waste mixed with plastic waste in the open environment is also a hazardous process. It is considered an inappropriate way of managing plastic waste, because of the emission of toxic gasses produced from the decomposition of plastic/PET molecular chains and additives. During the process, halogens in the plastics fraction form volatile metal halides, which, through catalytic effects, aid in the formation of dioxins and furans [42]. The adverse environmental impacts due to the incineration of plastic waste in the open atmosphere include the generation of airborne particulates and greenhouse gas emissions. Therefore, the open burning of PET and plastic waste is not practiced in many European countries, and all the waste is utilized in the recycling processes. The government of India also enforced a ban on the open burning of plastic waste [43]. The open burning of plastic and other solid waste is also prohibited in Sri Lanka, and the same is considered a punishable offense there [44].

4.3. Littering

Littering is another inappropriate way of disposing of plastic/PET waste. Such waste, which fails to reach landfills or incinerators, is identified as the cause of manifold ecological problems, such as the choking of water bodies, an impediment to the growth of flora and fauna, etc. The dumping of plastic waste into water bodies such as rivers or oceans contributes to the deaths of millions of seabirds, thousands of marine mammals, and countless fish every year [45]. The city of Mumbai, India experienced tremendous monsoon flooding in the year 2005, resulting in around 1000 deaths [46], and the same was blamed on plastic bags that choked the gutters and drains, preventing rainwater from draining

through underground systems. A similar tragedy occurred in 1988 and 1998 in Bangladesh, which led to the banning of plastic bag usage in 2002 [47]. Sri Lanka and other countries adopted a ban for similar reasons. Mauretania imposed a ban on plastic bags as cattle were getting sick from eating plastic bags. Indonesia, the world's second-biggest plastics polluter after China, has pledged to reduce plastic waste emission into the ocean by 75% by 2025. According to BBC News, South Africa and Cameroon have recently joined other countries to declare a tax on the use of thin bags to prevent the contamination of Africa's fields and cities.

5. Environment-Friendly (Sustainable) Methods of PET and Plastic Waste Management

Worldwide efforts are in progress to discourage practicing the above unsustainable disposal methods and develop environment-friendly (sustainable) methods to manage PET and plastic waste, which also results in the generation of some useful products.

Thermo-plastic wastes such as HDPE, PP, etc., are being used in bitumen road construction [48]. It was reported that about 1 ton of plastic waste in molten form is mixed with 5 tons of bitumen to construct 1 km of road. The usage of PET waste as a polymeric admixture to bitumen was attempted at a temperature of 200–220 °C. The same resulted in an increase in Marshall Stability by up to 76% at a dosage of 5.3% PET waste. An increase in the density and flow value of the mix was also reported [49]. Crushed PET waste and vehicle tire waste were used as fine aggregates in road construction [50,51].

Recycling PET and plastic waste is attracting worldwide attention as a sustainable option to manage the same. However, to implement these methods, it is necessary first to segregate PET and plastic waste from MSW (for waste-to-energy conversion), and segregate PET waste from plastic/PET waste (for material recycling).

5.1. Collection of PET and Plastic Waste from Source

To promote the collection of plastic waste before dumping it into MSW, people worldwide are encouraged to segregate their waste at the source as recyclable and non-recyclable waste, and deposit the same in separate bins placed at the roadside. Placing colored bins (such as blue, green, and yellow) at convenient locations in which such waste can be deposited is being widely adopted in many countries, such as the UK, Singapore, Germany, etc. Such a system is also practiced in many cities in India, such as Chennai, Mumbai, Bengaluru, Delhi, and Kolkata. The colored bins are also being made available to individuals on a yearly rent basis for the deposition of plastic waste, and these are collected once a week. An automated underground pipe system has been installed in some of the cities of the world, through which the waste deposited in colored bins in residential areas, business premises, town centers, hospitals, and airports is transported with the help of air (at a velocity of about 70 km/h) to a centralized processing plant. One such system is in operation in the city of Gandhinagar, Gujarat, India. However, the old practice of manual door-to-door waste collection on pneumatic vehicles is still in vogue in many cities of India.

Reverse vending machines, which accept used beverage cans and PET bottles and give cash in return, are in use in countries like the USA, Germany, Australia, China, etc. Sometimes, monetary incentives (in terms of mobile recharging, travel tickets, movie tickets, parking tickets, etc.) are being offered to encourage people to place used plastic bottles in collection bins. In India, the first reverse vending machine, which can accept and crush up to 500 bottles in a day, was set up at Church Gate Railway Station in Mumbai, India, on June 2015. Users will get an instant "reward" when used containers are fed into the machine, thus motivating them towards repeated use. When the device accepts the bottles, three options will appear on the screen; rewards, mobile recharge, and a discount from an outlet with which the machine provider has ties for concessions. The user can select any of the options, and a printout for the same will be issued. Bisleri, one of the largest bottled water manufacturing companies in India, and Inorbit Mall jointly started a PET bottle collection center in Inorbit Mall, Vashi, and Mumbai, India in February 2012. It is India's first ever plastic (PET) bottle collection and recycling machine (with no incentive).

5.2. Separation of Plastic Waste from MSW

5.2.1. Electrostatic Separator

This method is frequently used to separate directing and non-conducting constituents in MSW, and is usually applied to isolated aluminum or copper from plastics or paper [52]. Furthermore, a technique that uses eddy currents is also employed to separate plastic particles from metal and plastic mixture. These procedures are appropriate only to separate good conductors, such as metallic particles, from dielectrics, such as plastics. However, this method is unsuitable for separating dielectric particles such as mixed plastic combinations.

5.2.2. Triboelectric Separation

Triboelectric separation is a type of electrostatic separation that utilizes frictional charging. Its use for the separation of plastics is a relatively new approach. In this technique, electric charges are imparted to the particles of two polymers in a mixture, and then they are separated by passing through an external electric field [53]. The deposition of positive or negative electric charges on a polymer depends on its ability to hold or lose electrons. A material with a higher affinity for electrons gains electrons and gets negatively charged, whereas a material with a low affinity loses electrons and gets positively charged [54]. An air cyclone is employed as a charging device to produce a higher frictional speed, and a triboelectric cyclone separator has been developed, which has been successfully tested for separating plastics in the laboratory.

5.2.3. Air Separator

This method is common in recycling facilities to separate different materials from a waste stream, such as plastic bottles from aluminum cans. The method is based on the principle of density, where materials with different densities are separated by controlling the airflow generated by a fan. The process starts with the waste stream being fed into the separator. The measured airflow produced by the fan splits the waste into light and heavy fractions, with the light fraction being extracted upwards and the heavy fraction being separated into a second conveyor [55–57]. The less-heavy fraction then reaches a rotary valve, where the rotor reduces the airspeed and the fraction is discharged onto another conveyor. This separation method is efficient and cost-effective, as it allows for separating different materials in a single step, making it easier to recycle the different materials. However, it is important to note that the separation process's effectiveness depends on the waste stream's specific characteristics, such as the size and density of the materials.

5.3. Separation of PET Waste from Plastic Waste

The waste plastic consequently collected directly (as described in Section 4.1) or separated from MSW (as described in Section 5.2) is additionally separated from discrete PET in the rest of the plastic waste. There are various methods for separating PVC and PET from plastic waste, as they often look similar and are problematic to differentiate. One method is the use of spectroscopy methods, which employ different types of spectroscopy, such as FTIR and XRF, to identify different types of plastics/polymers. Another method is the use of dry separation techniques, which utilize different physical properties such as the density, size, and shape of the materials to separate them. Air separation, eddy current separation, and electrostatic separation are examples of dry separation techniques. Wet separation techniques are also employed for separating PVC and PET from plastic waste. The liquid medium is used to dissolve or soften certain plastics, making separating them easier. The disadvantage of wet separation techniques is that they require a post-sorting process for re-use or discharge, expensive reagents, and the drying/dewatering of the plastics extracted from the process [58]. It is important to note that the separation process's effectiveness depends on the waste stream's specific characteristics, such as the size and density of the materials, and the type of separation technique used (Table 4).

Table 4. PET waste separation from plastic waste.

Techniques	Tools/Process	Different Types of Recovered Materials	References
Dry Separation technique	Conveyor, resin/color detector, and air-jet ejector		[59–66]
	IR method for detection	FTIR	
		Acoust-optic tunable filter	
		Optical filter	
		IR with a diffraction grating	PET and PVC
	Raman spectroscopy		PET and PVC
InGaAsP laser diode		PET and PVC	[68,69]
	Air separator	PET and PVC	[57]
Wet Separation techniques		PVC/PET	[70–72]
	Flotation	Seven kinds of plastics, including (PVC, PET, PS, ABS, etc.)	[73]
	Sink–float method and selective Flotation technique	HDPE, PP, PET, PVC, PS, and ABS.	[74–77]

6. Methods of Management of Plastic Waste

6.1. Waste-to-Energy Conversion

6.1.1. Pyrolysis

Thermal depolymerization or pyrolysis is a process in which plastic/PET waste is heated to high temperatures (typically between 400 and 500 °C) in the absence of oxygen (in an oxygen-free environment) to break down the polymer chains and convert the plastic into smaller molecules. These smaller molecules can then be converted into various products such as gases (syngas), liquids (pyrolytic oil), and solids (char).

The syngas produced from this process can be used as a fuel source in boilers or engines to generate electricity. The pyrolytic oil can be used as a fuel for heating or feedstock for producing chemicals and new plastics. The solid char can also be used as a fuel or feedstock to produce activated carbon [78,79].

The main advantage of this process is that it allows for the recovery of energy from plastic waste and the production of new raw materials, which can be used to make new plastics, thus reducing the dependence on fossil fuels and the amount of plastic waste in the environment. However, this process is still in the research phase, and commercial applications are limited. The process is also expensive, and there is a need for more research to improve its efficiency and reduce the cost of the process [80,81]. It is considered green technology, as it does not contaminate water and the environment. Plasma Pyrolysis Technology (PPT) is a type of closed environment burning technique primarily used to burn medical waste. Still, it can also be used to burn plastic waste at high temperatures, such as 850 °C. A plasma-based pyrolysis system has been designed and put into use in the state of Gujarat, India for INR 1.2 million (Bhasin, 2009) [82].

A project entitled “Plastic Waste Disposal using Plasma Pyrolysis Technology” was funded by the Central Pollution Control Board (CPCB) and undertaken by the Facilitation Centre for Industrial Plasma Technology (FCIPT), Gandhi Nagar (Gujarat). The Institute for Plasma Research received funding to investigate the technology of plasma pyrolysis with economic support from the Department of Science and Technology (DST), and the New Delhi and Technology Information, Forecasting & Assessment Council (TIFAC). The study was supplemented by applying different kinds of waste plastic such as multilayer, metalized packaging, thin carry bags, etc. Throughout the experimentation, pollutant emissions such as dioxins, furans, particular matter (PM), oxides of nitrogen, and carbon monoxide were

observed (CPCB, 2016) [83]. In this method, the high maximum temperature was reached using a plasma torch in an oxygen-starved environment, which destroys plastic in an eco-friendly and efficient manner.

M/s Envac have installed waste treatment plants in many countries across the globe based on the pyrolysis process to produce biogas, liquid fuel, and bio-fertilizer. One such system has been in operation in the city of Gandhinagar, Gujarat, India, since April 2015. The controlled burning of waste to produce (electrical) energy is also being practiced worldwide. India's first commercial waste-to-energy plant with a handling capacity of 1300 tons of MSW per day and a production capacity of 16 MW energy has been in operation in Delhi, India, since 2010 (Westinghouse Plasma Corporation, 2014) [84].

6.1.2. Gasification

Gasification is the controlled burning of PET and plastic trash at temperatures between 600 and 800 °C in the presence of air or occasionally purified oxygen, with the latter approach being more expensive. Syngas, a combination of gases created through this process, is the initial result, and can be utilized as a fuel alternative to natural gas or as a source of raw materials for the manufacture of petrochemicals. Anke-Brems et al. (2013) have discussed the many technologies that are involved in the process, and how frequently a fluidized bed gasifier is employed for the purpose [85,86]. It should be noted that PET waste was also included in the plastic waste used in the operations above. Two plants built by M/s Westinghouse Plasma Gasification, each with a 1.6 MW capacity and able to consume roughly 72 tons of garbage per day [87], are located in the Indian state of Maharashtra.

6.2. Material Recycling

6.2.1. PET Recycling Techniques

The first report on recycling PET bottle waste came from the USA in 1977 [88], and since then, numerous investigations on PET recycling techniques have been conducted [89–91]. Used PET is being recovered at a steadily higher rate. With a rate of about 19.5%, PET leads the list of materials recycled from all solid plastic trash [21].

Mechanical Recycling

Mechanical recycling, also known as material recycling, primarily involves the washing of PET waste, followed by its crushing and grinding to reduce its size into flakes, re-extrusion into fibers, and the processing of the same for the production of new PET goods. There are two mechanical recycling methods that are currently in vogue for the production of fibers from PET waste:

1. A more common process for turning flakes into fibers is direct extrusion. Molten PET is extruded into a mold during the extrusion molding process, where it cools and solidifies to take the shape of the mold. For the production of huge products, PET extrusion molding is used. PET can be easily produced as an extruded material for bottles and jars;
2. The melt-extrusion process performed at 280 °C, where PET flakes are extruded into pellets or granules and then melt-extruded into fibers for extrusion molding (Bottle to Bottle PET recycling). It is worth noting that PET can be easily produced in the form of extruded material for bottles and jars, and blowing manufacturing can also be used for jars. This suggests that the same manufacturing process can be used for both bottles and jars made from PET. Technologies and plants are also available for the bottle-to-bottle process, in which PET bottle flakes are directly converted and then blown to make a bottle in an integrated system.

Chemical Recycling

Chemical recycling involves converting the PET chain by chemical processes into oligomers and other compounds. This process can be divided into two main categories: de-

polymerization and functionalization. Depolymerization consists in breaking down the PET chain into its monomers, which can then be used to produce new PET. Functionalization, on the other hand, involves chemically modifying the PET chain to produce new chemicals with different properties and applications [92–96]. One example of depolymerization is the process of methanolysis, in which PET is dissolved in methanol and heated to produce a mixture of terephthalic acid and ethylene glycol, which can be recycled to produce new PET. Another example is the process of glycolysis, which involves using a glycolysis agent to break down the PET chain into its monomers.

Chemical recycling can help reduce plastic waste's environmental impact, as it allows for the recovery and reuse of plastic materials, rather than relying on the traditional mechanical recycling process. However, it is an expensive process and requires specialized equipment and skilled personnel. It also poses a risk of pollution and the generation of harmful by-products.

In comparison to previous review papers on the management of polyethylene terephthalate (PET) plastic waste, our study offers several distinct contributions. While existing reviews have provided valuable insights into PET waste management practices, they often focus on general waste management techniques without a specific emphasis on PET waste, or lack a comprehensive analysis of regulatory frameworks and applications of recycled PET waste. In contrast, our study specifically concentrates on mechanical and chemical recycling methods for PET waste, exploring their advantages, limitations, and potential applications. Additionally, we delve into the rules and regulations implemented in different countries, shedding light on the varying approaches to PET waste management. Moreover, we examine the wide range of applications for recycled PET waste across industries such as textiles, packaging, and construction. These unique aspects differentiate our work from previous reviews and contribute to a more comprehensive understanding of PET waste management strategies [97].

Glycolysis is a chemical recycling process that involves the breaking down of PET into its constituent monomers, which are then used to produce new PET. This process typically involves heating the PET with a catalyst and a small amount of glycol, such as ethylene glycol or diethylene glycol. The glycol acts as a solvent and a reactant, helping to break down the PET and facilitate the formation of new monomers. The resulting monomers can then be purified and used to produce new PET. This method is found to be more environmentally friendly than traditional mechanical recycling methods (Table 5), as it allows for a greater degree of control over the final product and reduces the need for virgin raw materials. However, it is also more complex and costly, requiring specialized equipment and expertise [98].

Table 5. Chemical recycling techniques of PET waste.

Chemical Recycling Techniques	Reactant	References
Glycolysis	Ethylene glycol or diethylene glycol or propylene glycol dimethacrylated glycolysate	[99–104]
Hydrolysis	Water or acid or alkali	[105–108]
Methanolysis	Methanol	[109]
Aminolysis	Amine	[110–113]
Ammonolysis	Ammonia	[114]

In glycolysis, PET waste is chemically reacted with a diol, such as ethylene glycol, at high temperatures. The reaction breaks down the PET polymer into its constituent monomers, ethylene glycol, and terephthalic acid. These monomers can then be purified

and used as raw materials to produce new PET or other chemicals. The glycolysis of PET was first described in a patent in 1965 [115], and it involves the transesterification/glycolysis of a PET molecule with glycol and conversion of the same into a BHET molecule in the presence of transesterification catalysts. In this process, PET degradation is carried out using EG [116], DEG [117], propylene glycol, and di-propylene glycol [118] (Table 6). However, like glycolysis, a partial depolymerisation reaction resulting in an intermediate product, i.e., BHET and oligomers, can be used directly to produce new PET. It requires mild reaction conditions, such as atmospheric pressure and a temperature range of 180–250 °C. Therefore, attempts have been made for enhancing the rate of glycolysis and BHET monomer yield by use of efficient catalysts and the optimization of the reaction conditions, and these exertions have resulted in enhancements in BHET monomer yield and reaction time from 65% over 8 h to around 90%, and a reduced reaction time of about 30 min [118–120]. The most intensively studied method for increasing the glycolysis rate is the use of transesterification catalysts. Metal-based catalysts stimulate glycolysis reaction mechanisms [121,122].

Table 6. Glycolysis de-polymerization of PET by numerous reactions (Raheem et al. 2019) [6].

Catalysts	EG/PET Ratio	PET/Catalyst Wt. Ratio	T °C	Time Minutes	BHET Yield (%)	Reference
Zinc Acetate Lead Acetate Sodium Carbonate Sodium Bicarbonate	6:1 (m/m)	0.005	190	480	62.51 61.65 61.5 61.94	[123]
Zinc Acetate Titanium Phosphate	2.77:1 (m/m)	0.003	200	150	62.8 97.5	[124]
Zinc Acetate	5:1 (w/w)	0.01	196	180	85.6	[125]
Acetic Acid Lithium hydroxide Sodium sulfate Potassium Sulfate	6:1 (m/m)	0.005	190	480	62.42 62.50 65.72 64.42	[121]
B-zeolite γ -zeolite	6:1 (m/m)	0.01	196	480	66 65	[126]
Magnesium Chloride Ferric Chloride Lithium chloride Didymium Chloride Zinc Chloride	10:1 (m/m)	0.005	197	480	55.67 56.28 59.46 71.01 73.24	[122]
Sodium carbonate	2.45:1 (w/w)	0.01	196	60	78.94	[127]
SO ₄ ²⁻ /ZnO-TiO ₂	5.63:1 (w/w)	0.003	180	180	91.9	[128]
Y-Fe ₂ O ₃	3.7:1	0.0005	300	60	>90	[129]
Zn (OAc) ₂	6:1	0.002	208	150	85	[130]
Bmim ₂	4:1	0.2	175	90	95.7	[131]
(Mg-Zn)-Al	10:1	0.01	190	180	75	[132]
Nano ZnO	4:1	0.0005	190	80	90	[133]
Zinc Acetate TNT (Titanate Nanotubes)	4:1 4:1	0.0033 0.0033	196 196	120 120	82.6 76.7	[134]

6.3. Methods of Management of PET Waste

The management of PET waste involves various methods and strategies to minimize its environmental impact and promote sustainable practices. Here are some common methods of PET waste management:

1. **Recycling**—Recycling is a key method for managing PET waste. PET bottles and other PET products can be collected, sorted, and processed through mechanical or chemical recycling methods to produce new PET products or other useful materials. Recycling helps to conserve resources, reduce energy consumption, and divert PET waste from landfills;
2. **Waste separation and collection**—Effective waste separation and collection systems are essential for proper PET waste management. Establishing recycling programs, providing separate bins or containers for PET waste, and educating the public about the importance of recycling are crucial steps. Communities, businesses, and governments can work together to implement efficient waste collection systems;
3. **Extended producer responsibility (EPR)**—EPR is an approach whereby producers or manufacturers take responsibility for the entire lifecycle of their products, including proper disposal and recycling. By implementing EPR programs, manufacturers of PET products can design their packaging to be more recyclable, support recycling infrastructure, and take part in the collection and recycling of PET waste;
4. **Waste-to-energy conversion**—In cases where PET waste cannot be effectively recycled, waste-to-energy conversion methods can be considered. Technologies such as incineration or gasification can convert PET waste into energy sources like heat or electricity. However, it is important to ensure that these processes are conducted in an environmentally sound manner, and meet appropriate emissions standards;
5. **Education and awareness**—Educating the public about the importance of proper PET waste management is crucial. Promoting awareness campaigns, providing information on recycling practices, and encouraging responsible consumer behavior can help in reducing PET waste generation and increasing recycling rates;
6. **Reducing single-use plastics**—Addressing the root cause of PET waste involves reducing the consumption of single-use plastics. Encouraging the use of reusable alternatives, promoting sustainable packaging solutions, and supporting initiatives to phase out or limit single-use plastics can significantly reduce the amount of PET waste generated;
7. **Research and innovation**—Continuous research and innovation are important for finding new and improved methods of PET waste management. This includes developing advanced recycling technologies, exploring new uses for recycled PET materials, and finding ways to optimize waste management processes.

Implementing a combination of these methods, along with policy support and collaboration between various stakeholders, can contribute to the effective management of PET waste and the transition to a more sustainable circular economy.

7. PET Recycling Techniques

PET waste can be recycled using both mechanical and chemical recycling techniques. Mechanical recycling involves collecting and sorting PET waste, followed by shredding, washing, melting, and reprocessing the waste into new plastic pellets or fibers. This method is widely used and helps to produce various PET-based products. On the other hand, chemical recycling utilizes different processes such as glycolysis, hydrolysis, methanolysis, or solvolytic depolymerization to break down PET waste into its monomer building blocks, or other valuable chemicals. Chemical recycling offers the potential to recover high-quality monomers for PET production and address challenges associated with complex PET products (Table 7). Continued research and development efforts are being made to optimize both mechanical and chemical recycling techniques for PET waste recycling.

Table 7. Different glycolysis methods for PET recycling.

S. No	PET Glycolysis Methods	References	
1	Kinetics of PET waste glycolytic degradation.	[135–143]	
2	Theoretical and simulation research on PET glycolysis depolymerization.	[144]	
3	Microwave glycolysis depolymerization of PET.	[116,143,145]	
4	PET glycolysis depolymerization catalysts	Organometallic catalysts (heavy metal salt)	[119,127,136,146,147]
		Non-toxic metal salt (ionic liquid)	[147–149]
		Deep eutectic solvent catalyst	[150]
		Regenerable or recoverable catalysts	[151]
		Large-surface-area catalysts	[129]
	Other types of catalysts	[152]	

7.1. Mechanical Recycling

Mechanical recycling is the most common and widely employed method for recycling PET waste. It involves several steps:

1. Collection—PET waste, such as used PET bottles, is collected through recycling programs, waste management systems, or dedicated collection points. The proper collection and segregation of PET waste are crucial for effective recycling;
2. Sorting and cleaning—Collected PET waste undergoes sorting to separate it from other types of plastic and non-recyclable materials. The sorted PET waste is then thoroughly cleaned to remove contaminants like labels, caps, and residual liquids;
3. Shredding and granulating—The cleaned PET waste is shredded into smaller pieces or flakes. The flakes are then further processed into granules or pellets. Shredding and granulation increase the surface area of the PET material, making it easier to handle during subsequent processing;
4. Melting and purification—The PET flakes or granules are melted down to a liquid state in high-temperature extruders. During this process, any remaining impurities, such as dyes or additives, are filtered or removed. The purified molten PET is then cooled and solidified;
5. Reprocessing—The solidified PET material is usually cut into small pellets or chips, which can be used as feedstock in various manufacturing processes. These processes can include injection molding, blow molding, or extrusion to produce a wide range of PET-based products, such as fibers, films, sheets, bottles, containers, and packaging materials.

7.2. Chemical Recycling

The following Table 7 represents various methods of glycolysis used for the treatment of polyethylene terephthalate (PET) plastic waste. This table highlights different approaches used in glycolysis, such as kinetics of PET waste glycolytic degradation, the microwave glycolysis depolymerization of PET, etc., and Table 8 compares them based on key parameters including reaction conditions, catalysts used, reaction time, yield of monomers and temperature. The table provides a comprehensive overview of the different methods of glycolysis, enabling a comparative analysis of their effectiveness and feasibility for PET plastic waste management.

Relative Advantages of Glycolysis over Methanolysis and Hydrolysis

Glycolysis of PET is an area of widespread research because of the advantages of this process over methanolysis and hydrolysis, which include its suppleness, simplicity, low capital costs [153], eco-friendliness, and high yield. It also has a lower reaction time, and the process can be simply adapted to the conventional plants used for PET production. It stands out as the best PET recycling process over the other methods for the reason that it is

carried out in an extensive series of temperatures from 180 °C to 240 °C [118], and achieves the uppermost proficiency and eminence of the product when a catalyst is used [154,155]. Another additional benefit of glycolysis is that the BHET can be mixed with fresh BHET, and the combination can be used for other (DMT-based or TPA-based) PET production lines [105,115].

On the other hand, hydrolysis is comparatively easy compared to glycolysis and methanolysis. Among the three depolymerizing agents used in these three processes, i.e., water (hydrolysis), methanol (methanolysis), and ethylene glycol (glycolysis), water is the weakest nucleophile [8]. The other disadvantage of hydrolysis is the use of higher temperatures (200–250 °C) and pressures (1.4–2 MPa), besides a longer duration needed for depolymerization. Commercially, hydrolysis is not widely used to produce food-grade recycled PET because of the cost associated with the purification of the TPA produced during the process [140].

The main disadvantage of the methanolysis method is the high cost associated with the separation and refining of the mixture of the reaction products (glycols, alcohols, and phthalate derivatives). Furthermore, the water formed during the process causes a toxic effect on the catalyst, also causing the formation of various azeotropes. Also, with the existing inclination to use TPA, instead of DMT, as the raw material for the production of PET, the DMT produced by methanolysis must be converted into TPA, which significantly adds to the cost of the methanolysis process [156].

Mechanical vs. Chemical Recycling.

The relative advantages and disadvantages of mechanical and chemical recycling are presented in Table 8.

Table 8. Advantages and disadvantages of recycling methods.

Mechanical Recycling	
Advantages	Disadvantages
<p>Recycling PET by melt reprocessing is relatively simple, requires lower investments, utilizes established equipment [157,158], is flexible in relation to feedstock volume, and has little adverse environmental effect.</p>	<ul style="list-style-type: none"> (a) The foremost disadvantage faced in the melt reprocessing of any PET is a reduction in melt viscosity, which is caused by thermal and hydrolytic degradation [127]. (b) Melt reclaiming can produce cyclic and linear oligomers, which can affect the final product's features, such as printability or dyeability [159]. (c) Impurities such as polyvinylidene chloride (PVDC), PVC, glues, paper, ethylene-vinyl acetate (EVA), etc., produce acidic mixtures, which catalyze the hydrolysis of the PET's linkages of ester during thermal reprocessing [160]. (d) The yellowing of recycled post-consumer PET is another disadvantage. It could be due to intra-molecular cross-linking. Yellowing is sometimes a significant hindrance to the production of transparent recycled PET products.
Chemical Recycling	
Advantages	Disadvantages
<ul style="list-style-type: none"> (a) It does not involve the use of huge machines. (b) It may be more cost-effective than mechanical recycling. (c) Compared with mechanical recycling, chemical recycling conforms more to the principles of sustainability because it produces original raw materials. 	<ul style="list-style-type: none"> (a) The initial developing cost can be higher. (b) To be economically viable, chemical recycling methods need to be on a larger scale. (c) No published reports are available on the utilization of chemical recycling on an industrial scale.

8. Applications of Recycled PET (rPET) Products

Recycled PET goods have found numerous uses and are being employed in place of virgin PET. Table 9 indicates broad areas of applications of rPET [161], and as may be seen, large quantities of rPET are used to produce fibers.

Table 9. Application of rPET flakes.

Name of Product	Applications (%)
Fiber	38%
Food and Beverage Bottles	25%
Sheet and Film	24%
Strapping	7%
Non-food Bottles	4%
Other	2%

Table 10 presents some details of the application areas where products obtained from PET recycling are being used worldwide.

Table 10. Applications of products obtained from PET recycling.

Products from PET Recycling	Applications	References
rPET Fiber	<ul style="list-style-type: none"> • Cement concrete pavements as reinforcement: increases flexural strength and modulus of elasticity, and reduces plastic and drying shrinkage. Can also be used to improve structural properties depending on the size and diameter of the fiber • Textile: automobile seats, homes and office furniture, car roof. • PET staple fibers: carpets and rugs, fiberfill, and nonwoven fabrics. 	[162–168]
rPET Resin	<ul style="list-style-type: none"> • Construction: for the preparation of polyester polymer concrete with high compressive strength, flexural strength, and modulus of elasticity for use in repair works, joint, and crack filling. • Textile: automobile seats, homes and office furniture, car roof. • PET bottle manufacturing • Food and fruit containers • Cosmetic containers • Packaging materials • Enamel paints • Aqueous coating compositions • Epoxy-based paint 	[169]
rPET Pellets	<ul style="list-style-type: none"> • As aggregates in cement concrete 	[170,171]
rPET flakes	<ul style="list-style-type: none"> • As aggregates in cement concrete and polymer concrete • Bottle • Shoes and backpacks • Polar jackets 	[172–178]
Activated Carbon or Activated Charcoal	<ul style="list-style-type: none"> • Industrial application: in the metal finishing field • Environmental application: carbon adsorption has many applications in eliminating pollutants from air or water streams • Agricultural application: used as a pesticide, used in organic winemaking, etc. 	[179]
Hydrocarbon Liquid Fuel	<ul style="list-style-type: none"> • Transportation • Electric power generation. 	[180]
Polyester polyols	<ul style="list-style-type: none"> • Coating application on mild steel 	[181,182]
Polyurethane	<ul style="list-style-type: none"> • Tennis grips • Automobile part • Wheels • Rigid-hulls boats • Building insulation • Fridges and freezers: excellent insulators, low energy consumption, cost-effective • Wheels • Adhesives: especially as woodworking glue • Construction of sealant and fire stopping 	[183]
Polyurethane Foam	<ul style="list-style-type: none"> • Flexible foam: bedding, furniture, and automobiles • Rigid foam is used as an insulation material 	[184]
Urethane Oil	<ul style="list-style-type: none"> • Used as a varnish (wood surface coating material) 	[185]

9. Governmental Regulations for the Management of PET and Plastic/Waste

Keeping in view the growing volumes of plastic waste, concerted efforts were initiated long ago to manage plastic waste in many countries by formulating legal guidelines. As PET waste is a part of plastic waste, no separate guidelines for PET waste have been made. The Bureau of Indian Standards (BIS) issued an Indian Standard IS: 14534 in 2016 recommending different ways of plastic waste recycling, and suggested appropriate types of end-products that can be developed from plastic waste recycling (IS:14534, 2016) [186]. The Waste Framework Directive, revised in 2008, streamlined waste legislation, integrating rules on issues such as the management of dangerous waste and waste oils. The salient details of codal provisions for the management of MSW (plastic waste) set out in some countries are summarized in Table 11.

Table 11. Codes and regulations on MSW/plastic/PET waste in some of the countries.

Country	Act/Regulation/Policies	Salient Details	References
Australia	National Waste Policy-2009	<p>The policy aims to:</p> <ul style="list-style-type: none"> (a) Ensure that waste treatment, disposal, recovery, and re-use are undertaken in a safe, scientific, and environmentally sound manner (b) Avoid the generation of waste, reduce the amount of waste (including hazardous waste) (c) Contribute to a reduction in greenhouse gas emissions, energy conservation and production, water efficiency, and the productivity of the land (d) Manage waste as a resource (e) Plastics are included in the list of hazardous wastes, and hence unique treatment methods are advised for the same 	[187]
China	Waste Management in China: Issues and Recommendations—Urban Development Working Papers East Asia Infrastructure Department World Bank—Working Paper No. 9—May 2005	<ul style="list-style-type: none"> (a) Recommends aggressively pursuing a waste minimization program making it a key priority area in the management of solid waste (b) Advocates the 4R philosophy, i.e., waste reduction, reuse, recycling, and recovery, with waste reduction (c) Recommends improvements in the waste recycling industry with more professionalization, improved product standards, market development, and better operating standards (d) Recognizes the needs for additional landfills to cater to growing quantities of MSW and improve their operating conditions 	[188]
England	Environmental protection, England and Wales—The Waste (England and Wales) Regulations, No. 288, 2011	<ul style="list-style-type: none"> (a) Advocates a Waste Prevention Programme to reduce the generation of waste 	[189]
India	<ul style="list-style-type: none"> (1) G.S.R. 320 (E) [18-03-2016]: Plastic Waste Management Rules 2016 (2) S.O. 1357(E) [08-04-2016]: Solid Waste Management Rules, 2016 	<ul style="list-style-type: none"> (a) Stipulates individual responsibilities to all government bodies (central and state), municipal bodies, gram panchayat, as well as every waste generator, manufacturer, importer, retailer, producer, and street vendor, in a bid to control the menace of plastic waste (b) The rules prohibit the use of carrying bags (made of virgin plastic or recycled plastic) less than 50-micron thickness to discourage retailers from giving away carry bags (the higher cost of higher-thickness carry bags will deter the retailers from doing so) 	[190]

Table 11. Cont.

Country	Act/Regulation/Policies	Salient Details	References
Japan	Waste Management and Public Cleansing Law— Law No. 137 of 1970 (amended last in 2001)	<ul style="list-style-type: none"> (a) Plastic waste is categorized under industrial waste (b) Encourages individuals to set up (plastic) recycling plants (c) Municipal governments are in charge of disposing of urban waste, and the National Government provides funds to them for the implementation of the same under the law 	[191]
New Zealand	Waste Management Policy—First formulated in 1995	(a) Adopted the “Waste Generator Pays” approach and encouraged the use of a Waste Management Hierarchy	[192,193]
	Waste minimization act, 2008	<ul style="list-style-type: none"> (a) The Act aims to reduce the environmental harm of waste and provide economic, social, and cultural benefits for New Zealand (b) Based on the above act, Auckland City formulated its own “Auckland Waste Management and Minimization plan”, 2012. 	
South Korea	Korea Waste Management Law and Waste Disposal Forms—1991	<ul style="list-style-type: none"> (a) Regulations for reduction in waste products through the implementation of Extended Producer Responsibility (EPR) have been put into force. (b) The Korea Environment & Resources Corporation (ENVICO) was established to serve as a comprehensive waste management organization 	[194]
USA	Resource Conservation and Recovery Act (RCRA) 1976, with amendments from time to time.	(a) The principal federal law in the United States governs the disposal of solid and hazardous waste.	[195]
	Code of Federal Regulations—Title 40, Volume 26, Pt. 258)—2012	(a) Stipulates criteria for municipal solid waste landfills. The regulation deals elaborately with different aspects of landfills such as location restrictions, operating criteria, design criteria, groundwater monitoring, and correction	[196]
	Code of Federal Regulations—Title 40, Volume 26, Pt. 243)—2012	(a) Pertains to “Guidelines for the storage and collection of residential, commercial, and institutional solid waste”	[197]
Norway	Pollution Control Act 1981 (amended last on 20 June 2003)	(a) This Act aims to protect the environment against pollution and to reduce pollution, reduce the quantity of waste, and promote better waste management	Pollution Control Act 1981
Finland	Waste Act (646/2011)	(a) This Act aims to prevent the hazard and harm to human health and the environment posed by waste and waste management, to reduce the amount and harmfulness of waste, to promote the sustainable use of natural resources, to ensure functioning waste management, and to prevent littering	[198]
Slovenia	The Rules on Waste Disposal (2002)	<ul style="list-style-type: none"> (a) Increase the use of recyclable glass packaging (b) Separate collection of plastic packaging, especially beverage packaging (c) Separate collection of biological and green waste and their processing 	[199]

The discussion of this paper delves into the findings and insights generated by exploring the current techniques and approaches used for the management of polyethylene terephthalate (PET) plastic waste. The research question, “What are the current techniques and approaches used for the management of PET plastic waste, with a specific focus on mechanical and chemical recycling methods, rules and regulations in different countries, and applications of recycled PET waste?” guided our investigation and analysis.

Our examination of mechanical recycling methods revealed the significance of sorting, cleaning, and reprocessing techniques in recovering PET waste for reuse. We identified the advantages of mechanical recycling, such as its potential to reduce environmental impact, conserve resources, and contribute to a circular economy. However, challenges such as contamination, degradation, and limited recycling capacity were also noted, indicating the need for continuous improvement and innovation in this area.

The exploration of chemical recycling methods, including glycolysis, pyrolysis, and depolymerization, highlighted their potential for use in converting PET waste into valuable raw materials or feedstocks. These methods offer opportunities for closed-loop recycling and the production of high-quality materials, contributing to a more sustainable PET waste management system. Nonetheless, technological advancements, scalability, and cost-effectiveness remain areas for further research and development.

The discussion also assessed the rules and regulations implemented in different countries, underscoring the importance of policy frameworks in shaping PET waste management practices. Variations in regulations across nations were observed, reflecting diverse approaches to addressing PET waste challenges. Sharing best practices, harmonizing standards, and promoting international collaboration are essential for effective global PET waste management.

Furthermore, the applications of recycled PET waste in various fields were explored, highlighting the potential for utilizing these materials in sectors such as textile manufacturing, packaging, and construction. The adoption of recycled PET in these industries can contribute to resource conservation, waste reduction, and the development of sustainable products.

Overall, this discussion emphasizes the importance of an integrated approach to PET waste management, combining mechanical and chemical recycling methods, while considering the regulatory landscape and exploring diverse applications. It underscores the need for continued research, innovation, and collaboration among stakeholders to achieve a more sustainable and efficient PET waste management system on a global scale.

10. Conclusions

This article presents an overview of the current status of plastic production and consumption, and the share of PET in the same. The focus is on plastic waste disposal and management challenges, particularly for single-use PET items. The article highlights the various regulations in place in different countries for the disposal of Municipal Solid Waste (MSW) and plastic waste, and the methods of waste management that are sustainable and unsustainable. The article also reviews the modern methods of waste disposal that are being adopted worldwide and in India, such as mechanical and chemical recycling. Mechanical recycling, which includes washing, grinding, and pelletizing, is in extensive use due to its simplicity, established technical know-how, and lower investment. Although less popular, chemical recycling yields numerous chemical products that can be used in various applications. Thermal–mechanical recycling methods are also employed to generate electrical energy and fuel gas from plastic waste. The article emphasizes the importance of promoting sustainable development by making stringent regulations for dealing with PET and plastic waste. It also underlines the need for industries that produce this waste to take responsibility for its recycling and reuse, as it can be a profitable business. The end products of recycled PET are used in a wide variety of fields, such as cement concrete, the textile industry, the automobile industry, etc. The installation of new PET recycling plants

or the augmentation of the capacity of existing plants is taking place all over the world, and PET recycling is becoming a big industry by itself.

This study has explored and analyzed the current techniques and approaches used for the management of polyethylene terephthalate (PET) plastic waste. We have gained valuable insights into PET waste management practices. The examination of mechanical and chemical recycling methods, along with the discussion of rules and regulations in different countries, and the applications of recycled PET waste, provides a comprehensive understanding of the subject matter. This study emphasizes the need for integrated waste management strategies and sustainable practices to address the growing environmental concerns associated with PET plastic waste. The findings presented in this paper contribute to the existing knowledge in the field, and provide recommendations by which policymakers and waste management stakeholders can develop effective and sustainable PET waste management solutions.

In conclusion, the management and recycling of single-use PET and plastic waste is a complex issue that requires cooperation from governments, industry, and individuals. Through continued research and development, increased collection and sorting efforts, the promotion of the use of recycled materials, and the development of more efficient and cost-effective recycling methods, it is possible to improve the recycling rate and reduce the environmental impact of plastic waste. PET (polyethylene terephthalate) is a widely used packaging material due to its non-reactivity, durability, and shatterproof properties. However, this has led to an increase in PET waste generation, particularly in the form of single-use items. Recycling PET waste into useful products is considered an eco-friendly and sustainable method of waste management.

The current scenario of recycling techniques and management for single-use PET and plastic waste is a mixed one, with challenges such as contamination and a lack of proper infrastructure. However, there have been several efforts to improve the recycling of single-use PET and plastic waste, including the development of new recycling technologies, increasing collection and sorting, promoting the use of recycled materials, and improving awareness and education. Additionally, more efficient and cost-effective methods, such as chemical recycling, bioplastics, and proper recycling infrastructure, are needed to effectively manage and recycle single-use PET and plastic waste. Therefore, cooperation between governments, industry, and individuals is crucial to ensure the sustainable management of PET waste and to promote the use of recycled materials.

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Abbreviations

BRICS—Brazil, Russia, India, China and South Africa; BHET—Bis-2,hydroxy-ethylene terephthalate; CAGR—Compound Annual Growth Rate; CPCB—Central Pollution Control Board; DMT—dimethyl terephthalate; DEG—diethylene glycol; DSEWPC—Department of Sustainability, Environment, Water, Population and Communities; EG—ethylene glycol; EPA—Environmental Protection Agency; FMCG—fast-moving consumer goods; GBI—Global Business Intelligence; HDPE—high-

density polyethylene; kt—kilotons; PS/EPS—polystyrene/expanded polystyrene; MMT—million metric tons; MT—million tons; PET—poly(ethylene terephthalate); NAPCOR—National Association for PET Container Resources; PP—polypropylene; PVC—poly(vinyl chloride); rPET—recycled PET; RCRA—Resource Conservation and Recovery Act; TERI—The Energy Research Institute; TPA—terephthalic acid; TPD—tons per day.

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