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Polyethylene terephthalate waste derived nanomaterials (WDNMs) and its utilization in electrochemical devices

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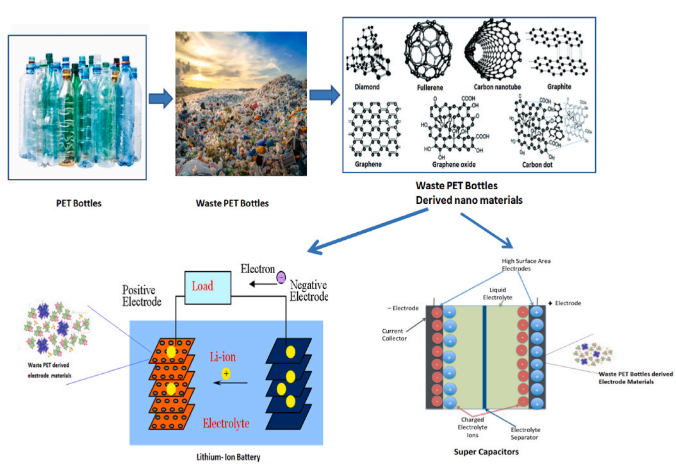
HIGHLIGHTS

- Accumulation of waste PET bottles and their adverse effect in Ecosystem.
- Importance of recycling of waste PET bottles.
- Various recycling methods of waste PET bottles.
- Synthesis of nanomaterials from Waste bottles.
- Utilization of synthesized nanomaterials in Energy applications.

GRAPHICAL ABSTRACT



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A B S T R A C T

Plastics are a vital component of our daily lives in the contemporary globalization period; they are present in all facets of modern life. Because the bulk of synthetic plastics utilized in the market are non-biodegradable by nature, the issues associated with their contamination are unavoidable in an era dominated by polymers. Polyethylene terephthalate (PET), which is extensively used in industries such as automotive, packaging, textile, food, and beverages production represents a major share of these non-biodegradable polymer productions. Given its extensive application across various sectors, PET usage results in a considerable amount of post-consumer waste, majority of which require disposal after a certain period. However, the recycling of polymeric waste materials has emerged as a prominent topic in research, driven by growing environmental consciousness. Numerous studies indicate that products derived from polymeric waste can be converted into a new polymeric resource in diverse sectors, including organic coatings and regenerative medicine. This review aims to consolidate significant scientific literatures on the recycling PET waste for electrochemical device applications. It also highlights the current challenges in scaling up these processes for industrial application.

1. Introduction

According to the United Nations Environment Programme, over 11.5×10^9 tonnes of solid wastes are generated annually. This amount of waste, particularly in developing countries where more than 90 % of rubbish is disposed of in an open way or burned, considerably contributes to environmental degradation and adverse health consequences (Ferronato and Torretta, 2019). Countries in Southeast Asia such as Malaysia, the Philippines, Vietnam, and Thailand, with weak waste management systems, suffer from massive imports of plastic, electrical, and electronic waste from industrialized nations. For instance, many recycling procedures for plastic and metal use hazardous chemicals for extraction and purification, creating new threats to the environment as well as human health. The economic value of the final commodities also has a direct effect on whether recycling and repurposing procedures are viable. To achieve both circularity and sustainability aims, it is desirable to use “clean manufacturing” methods to produce “value-added” goods from waste resources (Foolmaun and Ramjeeawon, 2012; Ferronato and Torretta, 2019; Ghoshal, 2019).

Plastic waste production has grown to be a serious global issue that negatively affects socioeconomic development and the environment. Every year, almost 300×10^6 tonnes of plastic garbage are produced, which is equal to the weight of the whole human population. Only 9 % of waste gets recycled; the remaining materials end up in landfills or the environment. Over time, these materials degrade into microplastics, small particles that facilitate the entry of pollutants into the air, freshwater systems, and human food chains. Coinciding with the rise in plastic production, there has been a notable increase in global plastic waste manufacturing. One of the most pressing challenges faced by the world today is the management of solid waste (Schwanse, 2011; Franz and Welle, 2020; Kibria et al., 2023).

The predominant constituents of plastics encompass synthetic polymers like polyethylene (PE), poly (ethylene terephthalate) (PET), polypropylene (PP), poly (vinyl chloride) (PVC) amd polystyrene (PS). These polymers find widespread utility in various sectors such as construction, packaging, agriculture, electronics, and healthcare, contributing to their substantial production and consumption. However, it has been reported that nearly 60 % of solid plastic waste ends up in landfills or open spaces on a global scale, primarily due to their extensive use and inadequate disposal practices. These disposable plastics have emerged as persistent environmental pollutants, emblematic of the anthropogenic waste generated by contemporary human society (Welle, 2011; Chamas et al., 2020). Beyond environmental contamination, mismanagement of plastic waste results in substantial economic losses, as a significant proportion of this waste lacks designated applications and is often improperly discarded in inappropriate locations like drains, unsanitary dumps, or landfills, particularly prevalent in developing nations (Dhaka et al., 2022).

Unquestionably, the prevalent utilization of non-decomposable plastics has led to a notable and demanding class of waste materials on the planet. Since a century ago, polymers have been widely employed to produce a huge variety of goods. According to Gu and Ozbakkaloglu (2016), the manufacture of synthetic plastics has actually expanded significantly during the past few decades. Traditional plastics endure and accumulate in the environment because they were made to be strong and resistant to changes in the external environment (Pol and Thiyagarajan, 2010). According to Schmaltz et al. (2020), plastics currently make up the majority of solid waste on a global basis. Alarmingly high levels of plastic waste and microplastics have been discovered in the water. By contaminating the trophic chain, these particles have an adverse effect on people in addition to aquatic life and birds (Ziani et al., 2023; Nkwachukwu et al., 2013; Eriksen et al., 2014). Plastic wastes (PWs) are hazardous because the colors contain very poisonous trace elements that could leave the polymeric matrix and enter the environment (Abdelbasir et al., 2020). This is in addition to the issues with their sluggish disintegration. Because of this, synthetic PW poisoning of the environment is today thought to be one of the most damaging and probably irreparable impacts of modern anthropogenic actions.

Due to its exceptional optical clarity, superior mechanical qualities, and brilliant thermoformability, PET is extensively used around the world despite its negative environmental impact. Fig. 1a shows the global PET bottle production for different applications. According to recent estimates, global PET demand would increase to 22.65×10^6 tonnes by 2025, valued at USD 44.1×10^9 (Smithers, 2020) Currently, PET packaging holds the largest market share in the Asia-Pacific region, at 36.7%. This is followed by North America with 20.5% and Western Europe at 17.9%. Additionally, the PET-based packaging industries in Middle Eastern and African countries are anticipated to experience significant growth from 2020 to 2025, buoyed by their developing socioeconomic conditions and expanding economies. In contrast, the U.S. Environmental Protection Agency’s 2018 report highlights a pressing issue in North America: the U.S. generated 35.7 million tons of plastic waste, constituting 12.2% of its total municipal solid waste. This volume includes a variety of plastic products, ranging from PET bottle waste to polyolefin and polyester bags, wraps, and containers. Notably, approximately 27 million tons of this waste, which accounts for 18.5% of the nation’s plastic trash, was relegated to landfills. Alarmingly, only a small fraction, about 4.5%, of plastic packaging was recycled (EPA, 2022). On the other hand, since 2000, the world’s energy consumption has grown by roughly a third, and it is anticipated to keep growing in the near future. Especially, global energy demand experienced a noteworthy growth of 2.9 % in 2018 alone. If current patterns remain unaltered, predictions indicate that by the year 2040, there will be a further 30 % surge in consumption, amounting to around 800 quadrillion British thermal units. This trajectory would consequently yield a substantial 77 % escalation in global energy consumption spanning the interval from 2000 to 2040 (Fig. 1b).

1.1. Plastic waste generation in India

As per reports from the fiscal year 2017–18, India's annual plastic waste production stands at approximately 9.4×10^6 tonnes, equating to a daily average of around 26,000 tonnes. Among this total, approximately 5.6×10^6 tonnes (equivalent to 15,600 tonnes per day) undergo recycling, while the remaining 3.8×10^6 tonnes either remain uncollected or end up as litter (amounting to 9400 tonnes per day). The issue of plastic waste generation is further reported to be escalating. Indeed, one of the most important reasons is that half of the plastic is discarded as waste after one-time usage. This rampant reliance on single-use plastic contributes to an increased demand for new plastic production, subsequently amplifying the associated carbon footprint (Geyer et al., 2017).

1.2. Harmful effects of plastic waste

Plastic is durable, strong, light, flexible, moisture-resistant, and fairly priced. These are the seductive qualities that tempt consumers to buy excessive amounts of plastic goods all over the world. However, plastic materials, which are tough and take a while to decompose, inevitably wind up in landfills despite being utilized to produce so many different products. A poisonous combination has been created by our strong attraction to plastic and our unavoidable behavioral predisposition to overconsume, discard, litter, and subsequently pollute (Kubowicz and Booth, 2017; Stanisavljevic and Brunner, 2019; Shojaei et al., 2020; Lange, 2021).

The disposal of plastic presents one of the most challenging and least comprehended aspects of its ecological impact. Ironically, the qualities of durability and resistance to deterioration are the most appealing features of plastic, which makes the disposal of plastic a great challenge for researchers. Further, the persistence of plastic poses a major concern due to the intricate synthetic chemical bonds within it, which prove to be challenging for natural organisms to break down (Ghatge et al., 2020; Das et al., 2021; Wojnowska-Baryła et al., 2022). Notably, less than 10 % of total plastic production is recycled, while the remaining 90 % accumulates in landfills, where it may remain inert for centuries, or subjected to incineration. Incineration toxic compounds into the atmosphere and leads to accumulation of these harmful substances within biotic forms within the surrounding ecosystems (Gwada et al., 2019a, b; Rubio et al., 2020; Borrelle et al., 2020; Rai et al., 2021).

1.3. Groundwater and soil pollution

Since plastic is a material that is meant to remain forever, its chemical composition prevents it from breaking down into ever-tinier pieces. Long periods of time go by with landfills holding untreated plastic garbage. Hazardous chemicals from plastics escape and seep into the groundwater, which then travel into lakes and rivers downstream. Recent studies have shown that anecic earthworms ingest microplastics in soil. Notably, these earthworms exhibited a decrease in growth rate after a 60-day exposure period to polyethylene microplastics, at a concentration of 0.2 %–1.2 % in the dry bulk soil. The emergence of microplastics in soil, attributable to plastic seepage is increasingly recognized as a source of soil pollution (López-Fonseca et al., 2011; Wang et al., 2012; Borrelle et al., 2020; Manam, 2022; Wei and Chen, 2023).

1.4. Pollution in oceans

The increasing volume of plastic present on the ocean's surface has resulted in more severe challenges. Owing to its gradual degradation rate, a significant portion of plastic waste that finds its way into marine environments remains afloat for many years, causing a decline in water oxygen levels and posing a threat to marine life. Plastic and other non-degradable materials are not amenable to recycling or absorption. The inadvertent consumption of plastic by marine organisms, particularly avian species, leads to instances of choking, which subsequently reduces

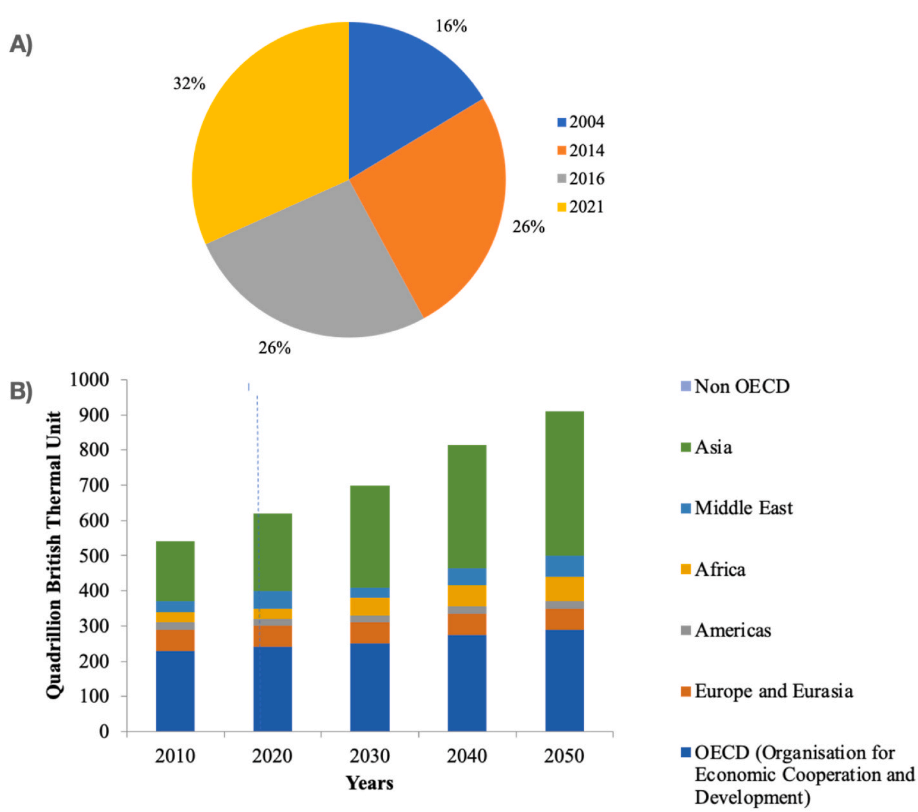

Fig. 1. (a) Global PET bottle production and (b) Global Energy Consumption.

the population of such creatures (Zhu et al., 2018; Navarro et al., 2023; Zhang et al., 2020). The adverse repercussions of plastic pollution on aquatic ecosystems are distressing and are exacerbating over time. In addition to causing suffocation, ingestion, and other forms of macro-particle-induced mortality among larger birds, fish, and mammals, plastic fragments are consumed by progressively smaller organisms as they fragment into tinier particles. This significantly results in the bioaccumulation of plastic in higher concentrations along the food chain, and thereby eventually affecting humans at the apex (Issac and Kandasubramanian, 2021; Ryan, 2016; Ali et al., 2021).

Microplastics, along with their hazardous components, are being ingested by even the smallest marine organisms, such as plankton, which play a crucial role in the ocean's ecosystem. These minuscule plastic particles, which degrade over time, are beginning to displace the algae vital for sustaining larger marine life that relies on them. Annually, an estimated 11 metric tonnes of plastic waste are deposited into the oceans, leading to the demise of marine life and the destruction of habitats. India is notably facing a severe challenge with oceanic plastic pollution (Lionetto and Esposito Corcione, 2021). The continuation of this trend poses a substantial risk, particularly affecting streams and further exacerbated when winds carry these plastics deeper into the ocean. One of the most polluted oceans in the world is found close to Mumbai, Kerala, and the Andaman and Nicobar Islands. Globally, plastic garbage has an influence on at least 267 species, including marine mammals (43%), seabirds (44 %) and sea turtles (86 %) (Vaid et al., 2021; Xin et al., 2021; Gwada et al., 2019a, b; Jambeck et al. 2015).

Recently, the disposal of PET bottles and other plastic waste into the ocean has led to a surge in the presence of microplastic debris. According to Thushari and Senevirathna (2020), the elimination of plastics from the aquatic environment addresses a crucial concern that has detrimental effects on the socioeconomic aspects of industries such as shipping, trawling, and fish farming. Due to their persistent and buoyant nature, microplastics have become a prevalent marine pollutant in aquatic surroundings, acting as carriers for the transfer of contaminants to aquatic organisms (Yang et al., 2021; Wi et al., 2011; Imran et al., 2011; Geng et al., 2015; Ali et al., 2021). Owing to their tiny size, microplastics are ingested by a variety of aquatic species, disrupting their physiological processes and subsequently transmitting through the food chain, ultimately impacting human health (Fig. 2). Many marine organisms rapidly absorb and expel microplastics, leading to lack of substantial evidence for biomagnification (Yuan et al., 2022; Alnaqbi et al., 2014; Padhan and Sreeram, 2019; Bianco et al., 2020). The consequences of microplastic ingestion include reduced food intake, behavioral anomalies, and developmental challenges.

The anthropological impact of microplastics significantly affects nearly 700 aquatic species internationally, including penguins, various crustaceans and sea turtles (Parsaeimehr et al., 2023; Astner et al., 2019). The trouble caused by microplastics worsens, but fewer victims are found in the broad oceans. It has been reported that human error or unchecked waste from water or sewage treatment plants and textile industries are the main causes of plastics entering the ecosystem. Further, due to insufficient landfill burial methods, the accumulation of terrestrial plastic eventually seeps into the water systems (Siddiqua et al., 2022; Vollmer et al., 2020; Dimitrov et al., 2013; Ji et al., 2020).

1.5. PET bottles in India

One of the broadly used plastics in India commercially is Polyethylene terephthalate (PET) bottles of varying shapes and sizes depending upon the usage. The molecular structure of PET and the synthesis root are depicted in Fig. 3(a) and (b). The thermoplastic polymer that is most frequently used worldwide is polyethylene terephthalate. According to IUPAC polymer nomenclature, PET's systematic structure classifies it as Poly (oxyethylene-oxyterephthaloyl). In the textile industry, it is commonly referred to as Polyester. Enhancements in material strength are often achieved by incorporating glass fibers or carbon. However, even in the absence of these additives, PET exhibits considerable strength relative to its lightweight nature. These attribute renders PET an efficient packaging material because it uses fewer resources during the manufacturing process. The use of PET packaging contributes to a minimal increase in the overall weight of the packaged item, thereby reducing fuel consumption during transportation. Furthermore, PET is characterized by its semi-crystalline, translucent, and almost shatterproof properties (Dhaka et al., 2022; Pinter et al., 2021; Johnson et al., 2021).

It is crucial to first comprehend the PET sector in India and how it has developed. By 2020, usage of PET resin have increased to 1.10×10^6 tonnes per year (TPA), growing by an average of 10–12 % annually. 94 % of it was bottles, while 6 % were sheets, straps, monofilaments, and other items. The anticipated increase in PET consumption in India is attributed to favorable demographic factors, such as urbanization and a young population. Initially, PET was utilized for carbonated soft drinks (CSD), edible oil, water, and jars. Today, it is essentially used in India for all end purposes. Fig. 4 illustrates the segmental usage of PET bottles in

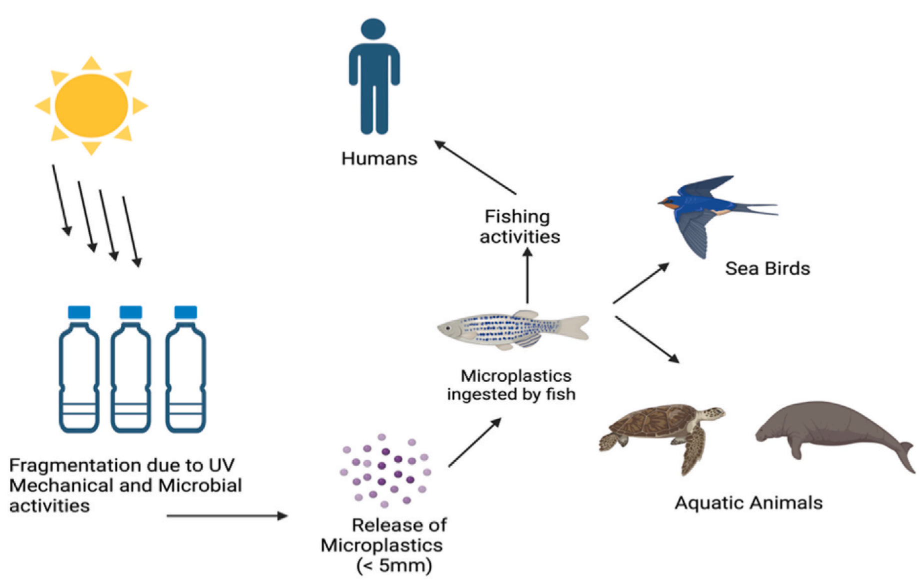

Fig. 2. Microplastics are ingested into the human by a variety of aquatic species.