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

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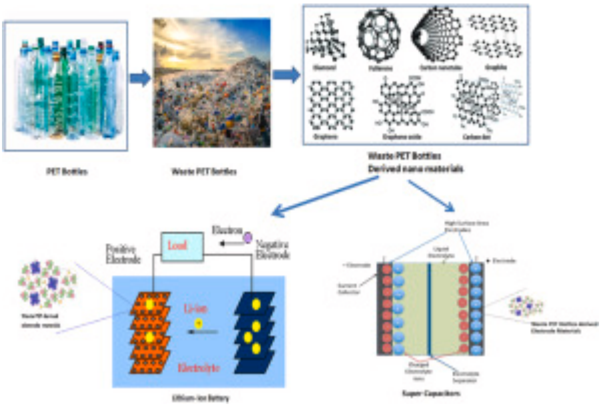
Highlights

- 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.

Abstract

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.

Graphical abstract



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).

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).

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).

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).

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 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).

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 India (Ivleva, 2021; Franz and Welle, 2020; Rodríguez-Hernandez et al., 2019).

To set waste plastics properly or to create new products, waste plastic management is a crucial step (Dutt and Soni, 2013). This section provides the conventional management techniques with their advantages and disadvantages. Fig. 5a and b provides a list of some crucial methods for managing waste plastics as well as the life cycle of PET bottles.

In most countries, the predominant approach to disposing of debris involves landfilling. This technique involves the utilization of stabilizers and antioxidants, which play a role in prolonging the biodegradation process of plastic waste polymers within landfills. However, landfilling does not seem to offer a suitable solution for effectively managing plastic waste. This is primarily due to the enduring nature of plastics, their slower biodegradation, the scarcity of available landfill locations, the complete depletion of raw materials, and concerns related to health, stemming from groundwater contamination due to the inclusion and leaching of harmful chemicals, and their ability to leach from landfills. Consequently, there is a need to restrict its application (Huang et al., 2022; Tournier et al., 2020; Evode et al., 2021; Kosmidis et al., 2001).

The substances present in rubbish are burned as part of a waste management process called incineration. Industrial facilities for waste incineration are usually referred to as “waste-to-energy facilities”. The term “thermal treatment” describes methods, such as incineration, for handling waste at high temperatures. The burning of discarded PET plastics causes an excessive discharge of particular matter and dangerous gases. Discarded PET bottles result in an excessive release of specific material and hazardous gases. Aldehydes, Olefins, and Paraffin, and short-chain hydrocarbons are amid with the volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) released during the incomplete burning of polystyrene (PS), polyethylene (PE) and polypropylene (PP). This could result in the emission of dangerous chemicals and high amounts of CO (carbon monoxide). Polyvinyl chloride (PVC) releases dioxins, carbon black, and aromatic chemicals including pyrene and chrysene, while burning plastic releases benzene, a VOC known to cause cancer. Halides and color pigments that include heavy metals including cadmium, lead, selenium, copper, chromium, and cobalt may also be released into the environment as hazardous compounds. As a result, incineration is also not considered (Verma et al., 2016; Mangold and von

Vacano, 2022; Singh et al., 2019; Kong and Hay, 2003).

Mechanical recycling involves transforming discarded thermoplastics into a new or related product type. Sorting the thermoplastic to be recycled is the first step in this type of primary and secondary recycling process. Most homogeneous thermoplastic waste is transformed into goods that are very similar to the original product. After being assembled from natural resources like crude oil, salt, natural gas and these materials are sent to petrochemical businesses where polymer experts produce plastics after a number of operations. The color, thickness, and size of the polymer are then altered before being sent to the customers. These products are disposed of after their initial life cycle. The first stage in mechanical recycling is gathering these waste materials. These products are sorted before being sent to recyclers, who attempt to turn them into new products. Following this, it is given to consumers once more, and the cycle continues. The recycling operation, however, is not efficiently feasible because it requires a lot of technology for sorting, energy to reform, cleaning, processing and ship as well as additional costs to carry out all of these processes in an environmentally acceptable way. The mechanical recycling of plastic waste first seems to be one of the “green” processes (Park and Kim, 2014; Koo et al., 2013; Astner et al., 2019).

To meet the growing demand for organic recovery, extensive research has focused on biodegradable polymers, necessitating the development of biological infrastructure with the requisite technical expertise. Processes like aerobic composting utilize aerobic bacteria, fungi, and other species that rely on polymers for nutrition and reproduction, aiding in the recycling of biopolymers. These organic carbon-containing materials are used to produce biomass, providing energy and environmental protection. In cases of complications, degradable polymers are segregated and treated separately from non-degradable components (Ahmed et al., 2018). Similarly, the biological recycling of PET involves enzymatic degradation to break down waste PET into its monomers, which are then bioconverted into value-added chemicals (Soong et al., 2022). This approach presents an environmentally friendly alternative to conventional recycling techniques. It not only recycles PET but potentially upcycles it, thereby fostering a circular economy with minimal environmental impact (Sadia et al., 2022).

Chemical recycling of PET, a major contributor to landfill waste, effectively decomposes this non-degradable plastic into its fundamental chemicals through processes such as glycolysis, pyrolysis, alcoholysis and reductive depolymerization. Advancements in material science and catalysis, particular the use of heterogeneous catalysts, have significantly improved PET depolymerization enabling the conversion of this material into monomers and other beneficial chemicals under milder conditions. This method marks a substantial industrial innovation in PET recycling, in line with ongoing developments and future directions in the sector (Zheng et al., 2023; Danso et al., 2019; George and Kurian, 2014; Geyer et al., 2016; Genta et al., 2005; Huang et al., 2011; Karim et al., 2022). Furthermore, chemical recycling plays a pivotal role in energy recovery, adhering to the principles of sustainable development. It is particular adept at processing mixed and contaminated polymers, reconstructing their deteriorated structures to meet the specifications and properties required for various end products, as highlighted by Karayannidis et al. (2006).

Techniques for PET recycling includes physical, enzymatic, and chemical recycling procedures (Ghosal and Nayak, 2022; García, 2022; Bohre et al., 2023). This includes a detailed description of various chemical reprocessing methods for PET, and the utilization of these chemically recycled products in developing novel, value-added NMs for electrochemical applications has been explored. A closed-loop sustainable ecosystem, which contributes to a cleaner world, could emerge from using these recycled products in a manner that is both environmentally sustainable and economically viable. Although several methods are available, but recycling by glycolysis is found to be more advantageous and reported to more suitable for large scale applications in particular for electrochemical applications.

Glycolysis of PET involves chemically breaking down PET polymer chains using glycols, such as ethylene glycol, in the presence of *trans*-esterification catalysts. Glycolysis eliminates the use of methanol, which is sometimes critical in methanolysis, and diminishes ecological footprint of recycling by not requiring strong acids or bases required in PET hydrolysis. The process is typically conducted under higher temperature over a duration of 0.5–8 h. This process effectively degrades the PET into smaller molecules, primarily yielding bis(2- hydroxyethyl) terephthalate (BHET) and other oligomers. These products can then be repurposed to manufacture various items like polyurethane foams and copolyesters (Sheel and Pant, 2019; Yang et al., 2022).

Recently, Shirazimoghaddam et al. (2023) conducted chemical recycling of PET through glycolysis, using niobia-based catalysts, demonstrating its potential as an effective solution to the escalating problems of plastic waste. This innovative approach involves depolymerizing PET into its bis(2-dydroxyethyl) terephthalate (BHET) monomer using ethylene glycol and niobia-based catalysts, notably sulfated niobia treated at 573 K. Remarkably, this process achieves a 100% conversion rate of PET and an 85% yield of BHET at a moderate temperature of 195 °C within 220 min. Such a method not only contributes to reduce the environmental impact of plastic waste but also promotes a more sustainable plastic economy by recycling PET using cost-effective, non-toxic catalysts under feasible conditions. Similarly, Asueta et al. (2023) applied glycolysis as a recycling method to depolymerize the complex PET waste, specifically the highly coloured and multi-layered fractions from household packaging. After initial sorting using near-infrared spectroscopy (NR) technology, which efficiently distinguishes PET from other materials like paper and cardboard, the more intricate PET fractions were targeted for chemical recycling. The effectiveness of the process was evaluated based on the formation and recovery of the monomer BHET and the quality of the resulting product. Notably, consistent and satisfactory outcomes in terms of monomer yield and quality were achieved, regardless of the specific type of complex PET waste treated, highlighting glycolysis as a viable method for recycling challenging PET materials. Likewise, Aguado et al. (2023) employed glycolysis to process both virgin PET and various types of PET waste, including highly coloured PET, multilayer PET, and municipal sorting waste PET. They used an excess of ethylene glycol and zinc acetate as a catalyst. Key factors influencing the glycolysis of PET waste, such as glycolysis temperature, duration, catalyst amount, and solvent quantity were extensively analyzed. The optimization of these factors for maximum yield was systematically investigated using a Taguchi orthogonal array method. This optimized process resulted in an impressive 79–88% conversion to the monomer. BHET under optimal conditions, demonstrating the efficacy of glycolysis in recycling diverse complex PET wastes and highlighting the potential for ethylene glycol recovery and reuse. Thus, glycolysis offers a sustainable, versatile and efficient solution for recycling PET, playing a crucial role in advancing sustainable waste management.

The conversion of plastic trash into molecules with industrial interest or the production of new materials with value additions in numerous industries remains a challenge despite the tremendous advancement of various technologies. The creation of new materials using recycled plastic as an aggregate can reduce waste, promote sustainable development, and aid the environment. Different methods can be used to produce these new materials, and each method is dependent on the quality and final use of plastic trash. Recently, Zhao et al. (2022) presented their work. Suggesting that leveraging plastic waste as a foundational resource for generating value-added commodities and/or nanomaterials could serve as a pivotal impetus for enhancing the attractiveness of plastic recycling. In the process of transforming plastic waste into these novel nanoparticles, several vital considerations come into play, as the integration of plastic waste might potentially impact the performance of the resulting NMs. In recent days, special attention has been directed towards finding alternatives to the utilization of plastic waste across diverse sectors, including construction materials, water treatment ultrafiltration membranes, 3D printing, and constituents in applications like asphalt, wallpaper, and the agricultural domain, among other fields.

Chemical recycling of used PET polymers as a supply material for nanomaterial synthesis is one of the most significant recycling methods. Because they are easily available, affordable, and abundant in carbon elements, they can be used to create useful materials that are based on carbon. Waste PET was successfully recycled chemically to create renewable unsaturated polyesters (Rorrer et al., 2019; Allen, 2019; Cao et al., 2022). It proved that creating high-performance polymers through the recycling of PET bottles and the use of products created from them was a creative process (Hou et al., 2021). The production of bulk carbon NMs from waste polymers with desired qualities, such as shape, nanodevices, electro emission, and metal replacement application, has attracted significant attention in recent years (Tiwari et al., 2022; Bratek et al., 2013). These carbon NMs offer a wide range of possible commercial applications; however, there are a lot of restrictions (Speranza, 2021).

Carbon, as one of the most abundant elements on the planet, has unique properties due to its hybrid orbitals. These hybridized bonds, which are produced by mixing atomic orbitals s and p to form new sp, sp2, and sp3 hybrid orbitals, result in a wide range of carbon allotropes spanning zero to three dimensions. One-dimensional carbon nanotubes, zero-dimensional buckyballs, two-dimensional graphene sheets, and three-dimensional diamonds are examples. These dimensional variations have garnered significant attention in the realm of nanotechnology applications (Onyancha et al., 2022; Adibfar et al., 2014; Al-Salem et al., 2009; Kaur et al., 2019). Materials act differently at the nanoscale than they do in bulk as a result of the effects of quantum confinement. Researchers from all over the world have convened to look into cutting-edge technological applications because these materials offer remarkable chemical, physical, and electrical properties when viewed from the standpoint of materials science. The type of end product obtained is known as nanoparticles (NPs), a category of materials that includes entities like fullerenes, carbon tubes, nanoshells, and quantum dots (QDs).

El Essawy et al. (2017) developed an eco-friendly method for converting PET bottle waste, a significant source of post-consumer plastic pollution into high-value nanostructure material. Their study presents a novel single-pot, solvent-free process for transforming PET waste into carbon nanostructure materials. It is simple, reproducible, and inexpensive to catalyze the thermal breakdown of PET waste in a closed reactor under autogenic pressure. The main innovation of their work is the acquirement of very valuable carbon nanostructured materials from PET waste utilizing a different, simple method that is equal to chemical recycling to ease disposal difficulties (Sinha et al., 2010; Chen et al., 2022). PET waste serves as an excellent source material for porous carbon due to its low impurity levels, eliminating the need for extensive pre-cleaning beyond simple washing to remove surface dirt and dust.

This results in activated carbon with a uniform and narrow micropore size distribution. The inherent purity of PET makes it an ideal raw material for producing carbon nanofibers, as further explored by Sharifian and Asasian-Kolur (2022). This research not only provides a sustainable solution to plastic waste but also contributes to the advancement of material sciences in creating valuable nanostructured materials.

Scientists from all around the world are interested in carbon quantum dots (CQDs) because of their fascinating photoluminescence behavior, low toxicity, high optical activity, and biocompatibility. The two main methods for creating quantum dots are top-down and bottom-up. CQDs can be produced using used PET bottles as a starting material (Wu et al., 2022; Wang et al., 2023a; Thirumalaivasan et al., 2024; Ramasubburayan et al., 2023; Chaudhary et al., 2021). To make nanoparticles, struck plastic debris is first dissolved in THF and then combined with water. The extra solvent was then expelled while the resulting nanoparticles, which had a diameter of 500 nm, were maintained at a temperature of 50 °C. To achieve particle separation, the nanoparticles were centrifuged and redispersed in MilliQ water. Chaudhary et al. (2021) produced fluorescent carbon a dot by simply heating plastic garbage made of bottles, old cups, and polyethylene bags. The resulting C-dots showed absorption peaks with sizes ranging from 5 to 30 nm at 260 nm. The structural alterations in plastic waste brought about by upcycling have also had an impact on the optical characteristics of C-dots.

A graphite sheet with a hexagonal pattern that has been wound around itself and placed in a horizontal container is the new carbon variety known as carbon nanotubes. Their longest length is 1 mm, and their diameters range from 0.4 to 100 nm. The matryoshka doll-like structure of the two types of carbon nanotubes-multiwalled and single-walled-is made up of multiple layers stacked axially inside of one another. There are several applications for carbon nanotubes. Since nanotubes have a much better mechanical toughness and current carrying capacity than metals, they are particularly well suited for use as interconnects in microelectronics. Because of their short radius of curvature at the tips, thin single-walled nanotubes are ideal for low-voltage emitting devices such as flat-panel displays. Many scientific domains have demonstrated the value of carbon nanotubes. Many different types of plastic trash were used to create carbon nanotubes (Fig. 6).

Wang et al. (2022a) produced organic solid-liquid phase change materials (PCM) from discarded PET bottles. These materials eventually acted as a precursor for the chemical vapour deposition (pCNT) procedure that is utilized to produce CNT. As a thermal management material, pCNT nanoadditives were doped into commercially available organic-based PCM to generate a pCNT-PCM nanocomposite. The PCM is fairly priced, has a high heat capacity, and a decent phase change temperature (42 °C), which is within the battery's operating range. A thorough investigation was carried out to discover how pCNT affected the thermal conductivity and heat capacity of PCM. The performance of the pCNT-PCM and cCNT-PCM composites was contrasted using the commercial CNT as a benchmark. The microstructure and thermal stability of the produced CNT-PCM nanocomposite were evaluated. Leakage tests using the CNT-PCM nanocomposite to investigate form stability were also included, along with a mechanistic and theoretical description of the behaviour of the nanocomposites. This study was the first to test the thermal performance of CNT manufactured from recycled plastic. In this case, it is predicted that the CNT created from waste plastic will replace commercial CNT and offer novel insights into the manufacture of pCNT. The predictable CNT-PCM composite has more potential for usage in thermal applications and is a formidable competitor for BTMS.

Graphene, the thinnest known structural variant of carbon, comprises a single layer of carbon atoms given in a two-dimensional nanosheet via sp^2 hybridization. Due to its advantageous mechanical, thermal, optical, and electrical attributes, coupled with its exceptional durability relative to other substances, graphene clutches noteworthy potential across a range of applications. El Essawy et al. (2017) successfully witnessed PET plastic bottle waste to produce graphene. The bottles were sieved and introduced into a Teflon-coated autoclave and exposed to 800 °C for 1 h, culminating in the spontaneous formation of graphene under ambient autoclave conditions.

Plastic waste is increasingly recognized as a rich reservoir of carbon precursors for divese applications, attributed to its high carbon content, ubiquity, and cost efficiency. Key polymers in this category include polyethylene and polypropylene (86 %), polyvinyl chloride (PVC) and polystyrene (92 %), polyacrylonitrile (PANI) (68 %), low-density polyethylene (LDPE), and polyethylene terephthalate (PET) (63%). Kigozi et al. (2023) explored a novel, emission-free method to transform PET plastic waste into high-quality carbon nanomaterials (CNMs), known as PT-nano powder, using a thermal-hydrothermal technique. The process, conducted above the glass transition temperature of PET, effectively converted PET plastics into PT-nano powder, characterized by 86.6% crystallinity and an average size of 6.5 nm. Spectroscopical methods confirmed the complete conversion of PET into carbon nanomaterials. Remarkably, when utilized in supercapacitors, the PT-nano powder demonstrated exceptional electrochemical performance. It exhibited a specific capacitance of 250.8 F/g, energy density of 34.83 Wh/kg, and power density of 999.9 W/kg at a current density of 0.5 A/g. Furthermore, the fabricated device maintained a high cycle stability with 96.8% capacitance retention even after 10,000 cycles at a current density of 1.5 A/g, showcasing its potential as an efficient and sustainable material for supercapacitor applications.

Wang et al. (2022b) employed a Metal-Organic Framework (MOF) derived from waste PET plastic for use as a lithium-ion battery (LIB) anode. Their research aimed to address the environmental issues caused by discarded PET bottles by repurposing them into CoNi-MOF, a prospective material for LIBs. The study involved the solvothermal synthesis of CoNi-MOF with varying Co/Ni ratios, specifically 0.5:1, 0.8:1, and 1:1, to determine the most effective MOF composition for LIB anode. Among these, the $Co_{0.8}$Ni-MOF produced from leftover PET plastic, demonstrated superior cycle stability, crystallinity, and electrochemical performance. The successful development of $Co_{0.8}$Ni-MOF as an electrode material holds significant potential in mitigating global warming and contributing to the development of a circular economy (Achilias and Karayannidis, 2004).

Kim et al. (2020) created a carbon anode material for LIB through the process of pyrolysis, employing waste PET as an additive along with fuel oil. By subjecting the materials to heat treatment, pitch was generated to serve as the intermediary substance for crafting carbon anodes. The incorporation of recycled PET into the mix contributed to elevating the pitch's softening point and bolstering its thermal stability. The assessment of electrical capacity involved the analysis of both defective cavities and engineered graphite interlayers. It was observed that a reduction in the La and Lc of the anode material resulted in an increased electric capacity within the cavity, attributed to a distortion in the graphite structure. The inclusion of waste PET accelerated the cavity capacity. By meticulously regulating the processes of heat treatment and PET in addition, the researchers achieved the production of anode material with notable efficiency levels surpassing 95% and demonstrating commendable C-rate performance (95%, 2C/0.1C). The exploration of the lithium-ion insertion mechanism centered on the influence of flawed cavities and intentionally fabricated graphite interlayers.

Recently, Wang et al. (2023b) developed a novel method for recycling PET plastics, in view of its environmental concerns and fostering sustainable development. PET plastics were degraded into terephthalic acid using NaOH in alcohol and ether solvents, achieving a 97% degradation rate at 80°C in 60min. This acid was then used to create monometallic and bimetallic CoZn-MOF materials. These materials demonstrated exceptional electrochemical performance, particularly the MOF-DMF/H_2O variant, which retained a high capacity after extensive cycling. This performance is attributed to the synergistic effects of Co2+ and Zn3+, rapid lithium-ion movement, and efficient electron transfer. Analytical techniques confirmed the role of organic ligands and electrostatic interactions in lithium storage, highlighting MOF's potential in lithium-ion batteries. This research contributes significantly to waste reduction and the development of advanced energy storage solutions.

Wang et al. (2022b) conducted an electrochemical analysis of newly created materials using 2025 size coin-type cells. These cells were designed with a lithium foil working electrode and a counter electrode, separated by a Celgard 2400 microporous membrane. The preparation involved mixing active materials, carbon black (Super P), and PVDF in a 7:2:1 ratio using N-methyl pyrrolidinone (NMP) as a solvent. The resulting mixture was spread on copper foil and vacuum-dried at 100 °C for 10 h. Cell assembly was done in an argon atmosphere glove box, ensuring minimal oxygen (0.5 ppm O_2). The electrolyte used was 1 M LiPF6 in a mixture of ethylene carbonate (EC) and dimethyl carbonate (DMC). Galvanostatic charge and discharge testing of the batteries was performed with a Neware battery tester, setting voltage limits between 0.01 V and 3 V. Cyclic voltammetry measurements were taken on a CHI 660a workstation at a scan rate of $0.2\,\mathrm{mV\,s^{-1}}$. The Co0.8Ni-MOF's charge/discharge profiles, as shown in Fig. 7a, were tested over several cycles at a current density of 0.5 A/g and voltage range of 3.0–0.01 V versus Li/Li+. The initial discharge and charge phases showed capacities of 2496 mAh/g and 1729 mAh/g, respectively, with a Coulombic efficiency of 69.27 %, indicating initial irreversible reactions likely due to SEI layer formation and electrolyte decomposition. The discharge phase showed distinct plateaus at 1.25, 0.95, and 0.55V, consistent with previous CV findings and suggesting consistent Li+ion insertion. Despite an initial decline in reversible capacity during the initial cycles, subsequent cycles achieved a nearly constant capacity of 1419 mAh/g.

Moreover, the stability of $Co_{0.8}$ Ni-MOF's electrochemical performance during consistent Li ion intercalation and deintercalation is evident in its charge-discharge curves remaining consistent from the 100 to 200 cycle. Fig. 7b provides a comparison of the galvanostatic charge and discharge profiles between $Co_{0.5}$Ni-MOF and $Co_{1.0}$Ni-MOF, both showing similarity to $Co_{0.8}$Ni-MOF under 500 mA/g in the first cycle process and substantiating the occurrence of identical redox reactions throughout the electrochemical processes. However, it was observed that the discharge (charge) capabilities of $Co_{0.8}$Ni-MOF were lower compared to $Co_{0.5}$Ni-MOF and $Co_{1.0}$Ni-MOF. This variation in discharge (charge) capacities results in Coulombic efficiency (CE) values of 1768 (1056) mAh/g and 2036 (1254) mAh/g for $Co_{0.5}$Ni-MOF and $Co_{1.0}$Ni-MOF, respectively. The cycling behavior of each CoNi-MOF sample is depicted in Fig. 7a, which highlights the continued superior performance of $Co_{0.8}$Ni-MOF in terms of capacity. Remarkably, even after 200 cycles, $Co_{0.8}$Ni-MOF maintains a reversible capacity of 1200mAh/g, a notable enhancement compared to the reversible capacities of $Co_{0.5}$Ni-MOF (750 mAh/g) and $Co_{1.0}$Ni-MOF (900 mAh/g).

As depicted in Fig. 7c, the $Co_{0.8}$Ni-MOF electrode consistently maintains a high Coulombic efficiency (CE) exceeding 99 % even after 200 cycles. This sustained performance, likely attributed to a gradual activation process arising from frequent lithiation and delithiation, enhances Li^+ transport kinetics over time. Remarkably, among all the CoNi-MOF samples, $Co_{0.8}$Ni-MOF exhibited the most remarkable rate capability, as illustrated in Fig. 7d. During tests at various current densities (0.1, 0.2, 0.5, 1, and 2 mA/g), the Co0.8Ni-MOF electrode exhibited average charge capacities of 914, 830, 713, 620, and 516 mAh/g, respectively. The capacity increased to 1113 mAh/g upon reverting to a current rate of 0.1 A/g. This increase is likely due to the electrodes activation through repeated charging and discharging, demonstrating the MOF structure's adaptability to rapid current changes. On the contrary, $Co_{0.5}$Ni-MOF and $Co_{1.0}$Ni-MOF provide only 531 and 401 mAh/g at 1 A/g, and 276 and 198 mAh/g at 2 A/g, respectively. Upon lowering the current density to 0.1 A/g, similar to the samples' initial capacitance, the capacities of $Co_{0.5}$Ni-MOF and $Co_{1.0}$Ni-MOF rebound to 945 mAh/g and 825 mAh/g, respectively. This recovery illustrates the MOF structures durability actross various charge-discharge cycles and current densities, maintaining consistent lithium storage efficiency. These findings suggest that among the tested MOFs, $Co_{0.8}$Ni-MOF exhibit promising qualities as an anode material for Li-ion batteries.

Goujon et al. (2021) introduced a cutting-edge method for chemically upcycling PET plastic waste, using it as a starting material for by anode production in energy storage device (Fig. 8). Their research demonstrated the feasibility of converting PET waste into redox-active polymer nanoparticles, which hold promise as anode materials in energy applications. The process involved converting BHET obtained from PET plastic waste via organocatalyzed chemical recycling, into a modified methacrylic monomer. This was followed by emulsion polymerization to produce methacrylic terephthalate polymer nanoparticles The electrochemical characteristics of the terephthalate precursor (BHET) were investigated in solution containing either a 0.1 M lithium bis(trifluoromethane) sulfonimide (LiTFSI) electrolyte or a 0.1 M tetrabutylammonium hexafluorophosphate ($TBAPF_6$) electrolyte. The performance of these redox-active polymer nanoparticles as anode materials was then assessed in a three-electrode cell set-up, using a 0.1 M $TBAPF_6$ electrolyte system.

In recent days, with a rapidly growing global population, the depletion of fossil fuels fossil fuel resources, and the accumulation of pollution-inducing industrial waste, there is high demand for research and development in the field of renewable energy and sustainable energy storage systems. Addressing the challenges, researchers are focusing on developing devices with enhanced energy density, improved power density, and extended life cycle. Within this framework, supercapacitors are receiving increased interest because of their outstanding performance. These include impressive power density values, raid charge-discharge capabilities, enhanced cycle stability, and cost-effective maintenance. Moreover, supercapacitors offer a prolonged lifespan (>100,000 cycles) and can operate efficiently across a wide range of temperatures, further bolstering their appeal for various power storage applications.

Supercapacitors are categorized based on their energy storage mechanisms and the materials used. Key types include pseudocapacitors, electrochemical double-layer capacitors (EDLCs), along with hybrid and battery-type capacitors. EDLCs function through electrostatic storage, utilizing reversible adsorption of electrolyte ions on materials with high specific surface areas. Common electrode materials for EDLCs include various carbon-based nanomaterials (CNMs) such as carbon quantum dots, carbon nanotubers, graphene, and 3D porous carbon. The capacitance of EDLC electrodes, both volumetric and specific, surpasses that of traditional electrolytic capacitors, owing to their large electrode surface area and the formation of a thin double layer. This characteristic endows EDLCs with superior power density and longer lifespans, a result of the non-destructive interactions at the electrode-electrolyte interface (Rahmanifar et al., 2018; Sahoo et al., 2015; Shinde et al., 2019; Qiu et al., 2017; Yi et al., 2015).

In pseudocapacitors, rapid and reversible redox reactions occur between the electrolyte and electroactive species on the electrode surface, making them well-suited for applications demanding high specific capacitance. Despite having higher energy densities compared to EDLCs, pseudocapacitors face limitations in longevity and power density due to phase changes in the electrode from faradaic reactions. Their operating potential window (OPW), typically around 1.2V, also influences their energy density. Pseudocapacitors employ a range of electrode materials, including redox-active transition metals in various oxidation states, metal oxides like FuO_2, FeO_4, NiO and MnO_2, and heteroatom-doped carbon materials. Conducive polymers, including polyanilines (PANIs), polypyrroles (PPYs), and polythiophenes are also employed (Kennedy et al., 2018).

Currently, electrochemical double-layer supercapacitors are prevalent in the market, favored for their cost-effectiveness, quick charging, long life, and low self-discharge rates, while pseudocapacitors represent a smaller portion. An innovative approach involves transforming waste PET bottles into electrode materials through suitable methods, as shown in Fig. 9. Zhang et al. (2021) utilized the post-activation pressure pyrolysis technique to convert PET waste into a methane-rich pyrolysis gas and carbon material suitable for energy storage. This method repurposes PET waste into an energy-storing materials, including methane-rich gas and carbon, through autogenic pressure pyrolysis and followed by activation. The resuting pyrolysis gas contains approximately 1.92×10^{-5} w% of CH_4. The pyrolytic carbon, further activated with KOH (AC-K), exhibited a significant specific surface area of $2683\,m^2/g$, a hierarchical porous structure, and various surface functional groups. The optimal EDLC behavior was indicated by the low-frequency vertical line in the Nyquist plot (Fig. 10).

El Essawy et al. (2017) developed a method to create graphene from discarded PET plastic bottles through a multistep process. The process began with crushing the plastic waste and sieving out micron-sized particles. The filtered material was then heated in a Teflon-coated stainless-steel autoclave at 800 °C for an hour. Graphene formation occurred as the autoclave gradually cooled to room temperature. This method offers a practical solution for converting plastic waste into graphene sheets. The procedure included controlled pyrolysis in a primary reactor at 400 °C, with a heating rate of 50 °C per minute to reduce hydrocarbon gas emissions. Further, graphene nano-sheets were generated at a higher temperature of 750 °C under an inert atmosphere, heating gradually at 10 °C per minute. This technique proved effective in creating hierarchically porous Carbon nanosheets (PCNSs) from various waste plastics like PP, PE, PS, PET, and PVC through catalytic carbonization and KOH activation. The resulting PCNSs displayed remarkable characteristics, including a specific surface area measuring $2198\,m^2/g$ and a pore volume of $3.026\,cm^3/g$. This successful process explores the potential for repurposing a range of waste plastics into valuable hierarchically porous carbon nanosheets. This not only contributes to waste reduction but also facilitates the synthesis of innovative materials.

Mu et al. (2020) effectively carbonized waste PET plastic to create three-dimensional (3D) porous carbon nanosheets (PCS) with a high yield of 36.4%. These PCS were then combined with MnO_2 nanoflakes to form PCS-MnO2 composites. After 24 h of stirring, 3.34 g of anhydrous aluminium chloride was added, followed by 10 g of ultrasonically dispersed silica particles. To complete the reaction, a mixture of acetone, HCl, and water in a 28.9:1 solution was incorporated into the system. The resulting mixture underwent centrifugation and repeated rinsing with ethanol before being dried in an oven. The final product was calcined for 3 h in the presence of N_2 at 600 °C. Any remaining silica was removed with a final HF treatment. To examine the kinetic characteristics of ion diffusion in the tested electrode materials, Nyquist plots were used. As shown in Fig. 10, the Nyquist plots consist of three distinct parts. In the high-frequency region, the intersection with the real axis corresponds to the combined series resistance (Rs) of the materials. The R_s values for PCS and the three PCS-MnO_2 composites were measured at 2.08 Ω, 2.23 Ω, 2.49 Ω, and 2.76 Ω, respectively, suggesting that the intrinsic resistance increases with additional MnO_2 on PCS. Moving to the mid-frequency range, the semicircle's diameter indicates the Rct of the electrode materials. The Rct values for PCS and PCS-MnO_2 composites were 1.07 Ω, 1.38 Ω, 1.6 Ω, and 1.73 Ω, respectively. The increased MnO_2 content in PCS reduced the pore width of the composite materials, which increased the distance for ion transportation, resulting in increased charge transportation resistance. In the low-frequency region, the curves become an inclined line, with a nearly vertical line indicating strong ion transport capabilities in the electrode materials. To Warburg coefficient “s" (ohm $s^{-1/2}$) was determined by fitting the real part of impedance (Z') against the −1/2 power of the angular frequency ($w^{-1/2}$) within the low-frequency range.

The capacity to replace virgin polymers with recycled plastic is determined by the amount of recycled plastic used and the purity of the recovered plastic feed. A major obstacle in producing high-quality recycled resins from plastic waste is the inherent incompatibility among various plastic types. This incompatibility arises from molecular immiscibility and differing processing requirements at a larger scale. For instance, the presence of even a small amount of PVC in a PET recycling stream can lead to the degradation of recycled PET resin due to the formation of hydrochloric acid gas at high temperatures necessary for melting and reprocessing PET. Consequently, integrating recovered plastic into new polymer products often leads to compromises in certain qualities of the virgin plastic, such as color, clarity, or mechanical properties like impact strength. Common practices in recycling include mixing recycled resin with virgin resin, typically in applications like polyolefin films for non-essential uses such as trash bags and non-pressure-rated irrigation or drainage pipes, or using recycled resin encased between layers of virgin resin.

Section snippets

Conclusion

PET plastic waste poses a significant challenge in today's world, significantly impacting both terrestrial and aquatic ecosystems through the spread of microplastics. The presence of microplastics is increasingly evident in all ecosystems, notably infiltrating even the depths of the ocean's due to their non-biodegradable nature. Although various recycling methods have been developed, each has its own drawbacks and limitations. There have been numerous efforts to repurpose discarded plastics

CRediT authorship contribution statement

J. Manjunathan: Conceptualization, Writing – original draft. **K. Pavithra:** Conceptualization, Writing – review & editing. **Senthilkumar Nangan:** Formal analysis. **S. Prakash:** Software. **Kuldeep K. Saxena:** Validation. **Kuldeep Sharma:** Validation. **Khursheed Muzammil:** Formal analysis. **Deepak Verma:** Validation. **Jenita Rani Gnanapragasam:** Software. **R. Ramasubburayan:** Supervision, Writing – review & editing. **M. Revathi:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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