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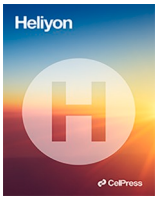

Review article

A comprehensive review of PETW recycling for supercapacitor applications

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ABSTRACT

The rising measure of waste produced from polyethene terephthalate (PET) and the interest in eco-accommodating energy storage arrangements have prompted escalated examination into reusing waste PET into supercapacitors. This review aims to provide a comprehensive overview of the most recent advancements in the recycling of polyethylene terephthalate waste (PETW), as a supercapacitor electrode precursor. The review looks at different methodologies for recovering PET from waste, including mechanical, chemical, enzyme, etc. It further explores the combination strategies for electrode materials produced using PET. Besides, PET-derived materials' electrochemical performance in supercapacitor application is likewise broken down, with an emphasis on key electrochemical boundaries like capacitive behaviour, cyclic stability, and electrochemical impedance spectroscopy. The need for scalable and cost-effective recycling methods, the creation of eco-friendly electrolytes, and the improvement of the electrochemical performance of recycled PET-based supercapacitors are just a few of the issues and opportunities highlighted in this expanding eco-friendly industry. Overall, the goal of this review is to provide a comprehensive understanding of the cutting-edge developments in the use of recycled PETW as a precursor for supercapacitor electrodes, highlighting the eco-friendly energy storage solution's potential and contributing to a sustainable future.

1. Introduction

Storing energy involves transforming it from challenging to easier forms. This is done using supercapacitors, thermal storage, pumped hydro, batteries, and other technologies. The main purpose is to balance supply and demand and improve power system reliability [1–3]. Supercapacitors use various materials, including waste materials, to achieve high energy and power densities. Waste-derived materials such as biomass, agricultural waste, paper, wood waste, industrial waste, electronic waste, textile waste, and plastic waste are being investigated for use as supercapacitor electrode materials with positive results [2,4,5].

Polyethylene terephthalate (PET) is a type of plastic commonly used in food and beverage containers and various packaging materials. The recycling of PET waste (PETW) has become an aspect of waste management due to the growing concerns surrounding sustainability. Managing PETW is an issue that requires sustainable recycling solutions in the long term [6–8]. PET is a plastic widely

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List of abbreviations including units and nomenclature

(PET)	Polyethene terephthalate
(PETW)	polyethene terephthalate waste
(TPA)	terephthalic acid
(MEG)	monoethylene glycol
(DMT)	dimethyl terephthalate
(HC)	hydrocarbon
(NIR)	near-infrared
(DMC)	dimethyl carbonate
(MOFs)	metal-organic frameworks
(SC)	supercapacitor
(EDLCs)	electrostatic double-layer capacitors
(AC)	activated carbon
(KOH)	potassium hydroxide
(PVDF)	polyvinylidene fluoride
(SEM)	scanning electron microscopy
(XRD)	X-ray diffraction
(PANI)	polyaniline
(PPy)	polypyrrole
(PEDOT)	poly(3,4-ethylenedioxythiophene)
(ESR)	Equivalent series resistance
(HTC)	Hydrothermal carbonization
(LIG)	laser-induced graphene
(CV)	cyclic voltammetry
(GCD)	Galvanostatic charge-discharge
(CBMs)	Carbon-based materials
(TMOs)	Transition metal oxides
(CPBMs)	Conducting polymer-based materials
(PBMs)	Perovskite-based materials.

utilized in products such as drink bottles, food containers and polyester fabrics. The challenge lies in the lasting nature of PET waste, which can take over 500 years to decompose naturally contributing to the accumulation of PETW in landfills, oceans and ecosystems [9–11]. Improper disposal and recycling practices further exacerbate this problem posing threats to wildlife, ecosystems and habitats [8,12]. With the increase in PETW production due to its use there is a pressing need for more efficient methods to recycle PETW bottles for both technological advancements and environmental protection reasons. Consequently, there is a growing demand for researchers to develop improved techniques, for recycling PETW bottles for sustainable development [13–15].

There are several significant reasons why PETW requires long-term recycling solutions. To begin with, recycling PETW reduces the requirement for virgin plastic, it also contributes to a decrease in the amount of fossil fuels, energy, and natural resources required to produce new plastic. Second, recycling PETW helps to reduce the environmental damage caused by plastic pollution, by keeping PET out of landfills and the environment, recycling PET effectively reduces rubbish and the negative effects it has on ecosystems and habitat species [16,17]. The process of recycling PET entails gathering, classifying, and turning wasted PET items into raw materials which can be used to create new products. This recycling process offers sustainable and affordable options, and ongoing research and advancements in PET recycling technology continue to support the development of creative approaches towards a more sustainable future [18,19]. This closed-loop method lessens waste production and saves resources, promoting a more resource-wise and sustainable value chain circular economy [7,15,20].

The issue of PETW on a global scale has given rise to several projects and policies that support long-term recycling solutions. These include (i) recycling infrastructure improvements to improve the collecting, sorting, and processing of PETW. As well as investments by governments, businesses, and organizations in the building of dependable recycling facilities. Improvements to infrastructure make recycling more effective and encourage individuals to participate in recycling activities [19,21]. (ii) the use of public awareness and education to inform people about the value of recycling PET and the right ways to dispose of it. The amount of PETW that ends up in landfills and the environment can be greatly decreased by encouraging responsible consumer behaviour and recycling practises [18, 22]. Researchers and industry professionals are investigating innovative recycling solutions to increase the effectiveness and efficiency of PET recycling. These include mechanical recycling, which entails melting PET and reforming it into new goods, as well as chemical recycling, which disassembles PET into its monomers for reuse [23–25]. Recycling PET finds usage in fabrics, packaging, and the textile sector. In films, it is also used to mould components for automobiles, electronics, energy storage and many other things [26,27]. With the use of porous carbon nanostructures derived from PETW, energy storage can meet the demand for trustworthy gadgets that have a rapid charge and slow discharge on a worldwide scale.

There are numerous advantages to recycling PET waste into materials for use in supercapacitors. PETW is a readily available raw

material that can be engineered to have high surface area and porosity, which is essential for storing more charges. Materials derived from PETW exhibit good chemical stability, ensuring reliable performance over time. Additionally, PETW-derived materials are more commercially viable as they can be produced at a lower cost compared to high-performance materials such as metal oxides or graphene. Apart from addressing environmental concerns, the use of PET waste-based materials in supercapacitors offers a dependable, high-performance, and reasonably priced alternative to conventional electrode materials. Therefore, they represent a viable choice for future energy storage technologies.

There has been some research on converting PETW into supercapacitors, covering material development, scalability, safety, versatility, security, and performance optimization. Be that as it may, with the new technological advancements there exist a lot of chances for additional investigation around this area. By consolidating state-of-the-art methods for the different processes engaged with the transformation of PETW into supercapacitors, we can improve the productivity, adequacy efficiency and effectiveness of this process. The goal of this review is to provide a comprehensive assessment of the most recent developments and research in the recycling of PETW for use in supercapacitors. This incorporates looking at the present status of the PET recycling systems, supercapacitor fabricating techniques, and the performance of PET-based supercapacitors. The review also included information on the performance of supercapacitors using recycled PET as feedstock for electrode material from published works. It also investigates various surface modification strategies, processing techniques, and hybrid material approaches to enhance the electrochemical performance and stability of supercapacitor electrodes. In addition, it looks at the possible environmental advantages of recycling PETW for supercapacitors, pointing out any potential disadvantages and areas for improvement.

2. PETW recycling processes and techniques

PETW recycling entails a variety of techniques that convert discarded PET materials into valuable products. These techniques are roughly classified as mechanical recycling [26,28], chemical recycling [16,24], and depolymerization [23,29]. These recycling methods are critical in decreasing the environmental impact of PETW and supporting a circular economy. Although each recycling method has its advantages and disadvantages, the recycling strategy selected is determined by criteria such as the quality and type of PETW, the intended end products, and the availability of infrastructure and technologies for certain recycling processes [8,30].

Mechanical recycling of PETW entails physically separating, grinding, and melting PETW to create new products. It consists of several steps, including sorting, in which the PETW is sorted based on colour and resin type to remove contaminants and ensure a consistent feedstock [23,26,28]. The next step is shredding or grinding, in which the sorted PETW is shredded into flakes or granules, followed by the washing step where the shredded PET flakes undergo multiple washing steps to remove any impurities or residual contaminants such as dirt, labels, and adhesives. The washed flakes are then separated from impurities using techniques such as density separation or air classification in a separation step. The final step is melting and extrusion, in which the purified PET flakes are melted and extruded into pellets or granules that can be used as feedstock for various applications such as the production of new PET products or as precursors for other recycling processes [13,31]. Mechanical recycling is widely used in many recycling facilities, which have a well-established infrastructure, and use less amount of energy compared to other recycling processes. Due to its developed technique and established market for recycled PET products, it is often a cost-effective approach. Nevertheless, the mechanical recycling of PETW is also fraught with challenges. The quality of the recycled PET material is its main flaw, as it may deteriorate because of repeated melting and processing, which would limit its suitability for applications requiring high-quality PET. In addition, it is prone to contamination since contaminants and various plastics might impair the recycled PET's quality. Furthermore, the availability of recycled PET in particular may be restricted by the sorting step in mechanical recycling [19,23].

Chemical recycling entails breaking down PETW into its chemical components via various chemical processes to produce fresh PET or other valuable chemicals. Glycolysis, hydrolysis, methanolysis, depolymerization, and pyrolysis are some popular chemical recycling methods for PETW [32,33]. Glycolysis is the process of breaking down PETW into its monomers - terephthalic acid (TPA) and monoethylene glycol (MEG) - using a high-temperature glycol solution (typically ethylene glycol). To enhance the reaction between PET and glycol and produce bis(2-hydroxyethyl) terephthalate (BHET, an ester of terephthalic acid and ethylene glycol) and oligomers with different chain lengths, the glycolysis process is typically carried out between 180 °C and 240 °C. After the depolymerization process is finished, the reaction mixture is cooled and purified by filtration, crystallisation, or distillation, which is then recovered and used as feedstock to produce new PET or other chemicals [34–37]. Hydrolysis is a method that breaks down PETW into its constituent monomers by treating it with water or steam at elevated temperatures and pressures. The monomers can be refined further and used in PET production or other applications. Methanolysis is when PETW is treated with methanol in the presence of catalysts to produce dimethyl terephthalate (DMT) and ethylene glycol. The DMT can be then used for PET production [38,39]. In general, chemical recycling methods have the potential to generate high-quality recycled PET that is similar to virgin PET, the resulting monomers or chemicals can be used for various applications beyond PET production. The method can manage mixed waste streams, allowing for the recycling of PET with other plastics. However, chemical recycling processes face the challenges of greater complexity and lower technological maturity when compared to mechanical recycling. They are also faced with technical and economic challenges, requiring further development and optimization, and some may need significant energy inputs, especially those involving elevated temperatures and pressures [40]. Scaling up chemical recycling processes and making them cost-competitive with mechanical recycling can be challenging. Efforts are being made to develop and optimize these recycling methods to improve the efficiency and sustainability of PETW recycling [40,41].

The depolymerization process involves chemically breaking down the polymer chains of PETW into their constituent monomers or smaller oligomers, which can be accomplished using a variety of methods such as chemical solvents [34], catalysts [42,43], or enzyme reactions [29]. Enzymatic depolymerization is when enzymes catalyse the breakdown of PET into monomers. This approach appears to

be promising, although it is still in its early phases of development. Pyrolysis, on the other hand, is the thermal degradation of PETW in the absence of oxygen. The procedure produces a mixture of products, including gases, hydrocarbon (HC) compounds, liquids, and char, a carbon-rich solid residue [44,45]. The HC product of pyrolysis can be used as a fuel or feedstock for chemical processes, the liquid and gas fractions can be refined further or used for energy generation, and the char can be used as a carbon source or converted into activated carbon for several applications, including energy storage devices such as supercapacitors [46–48]. Depolymerization methods have the potential to produce high-quality monomers that can be used for PET production and can generate a range of valuable chemical products beyond PET, offering diverse recycling opportunities. The process can manage PETW with various additives and contaminants. However, depolymerization technologies are still in the early developmental stages and may require further research and optimization before commercial viability. Furthermore, the process may currently be more energy-intensive and expensive than other recycling methods, making them less economically viable. Enzymatic depolymerization, although promising, is currently limited by enzyme efficiency, reaction rates, and cost-effectiveness [49].

The conversion of PETW into raw materials for the manufacturing of chemicals or fuels is known as feedstock recycling, sometimes known as advanced recycling or chemical conversion. PETW can also be converted into syngas or liquid fuels using advanced recycling techniques such as gasification or hydrothermal liquefaction, which can then be processed or utilized in industrial operations [50].

2.1. Recent advancements in PETW recycling techniques

The efficiency and sustainability of PETW recycling systems have seen some significant advancements, such as enhanced mechanical recycling, advanced chemical recycling, supercritical fluid recycling, etc [27,51–56]. Advanced and new sorting technologies, such as near-infrared (NIR) spectroscopy and hyperspectral imaging, have been developed to improve the accuracy and efficiency of PETW sorting, reducing contamination in mechanical recycling techniques [57]. Innovations in process optimization (grinding, cleaning, and extrusion processes) have led to improved quality of recycled PET and reduced energy consumption during mechanical recycling. The incorporation of additives, such as compatibilizers and chain extenders, into the recycling process, has shown promise in enhancing the mechanical properties of recycled PET, allowing for broader application possibilities [27,31].

Advanced solvent-based processes, such as dimethyl carbonate (DMC) and ionic liquid methods, have been explored to efficiently depolymerize PETW, achieving high-quality monomers for PET production [16,39]. Innovative catalytic conversion processes using various catalysts, including zeolites and metal-organic frameworks (MOFs), have shown potential to improve the efficiency of chemical recycling by reducing energy requirements and enhancing product yields [40,58]. Microwave-assisted depolymerization techniques have been investigated as a rapid and energy-efficient method to break down PETW into valuable chemicals [43,47,54,59]. Moreso, there are ongoing research efforts focused on developing enzymes with improved efficiency, stability, and specificity for PET depolymerization [45]. Protein engineering techniques, such as directed evolution and computational design, are being employed to create enzymes with enhanced performance [44,49,60]. Scientists are also working on optimizing reaction conditions, such as temperature, pH, and reaction time, to improve the enzymatic depolymerization efficiency and reduce the cost of the process. At the same time, strategies are being explored to recover and reuse enzymes, improving the overall sustainability of enzymatic depolymerization.

The use of supercritical fluids, such as supercritical CO_2, offers a solvent-free and energy-efficient method for PETW recycling, allowing for the selective recovery of high-quality PET and other valuable components are also being explored [61,62]. Innovative pyrolysis techniques, such as microwave-assisted pyrolysis and catalytic pyrolysis, are being developed to improve the yield and quality of the pyrolysis products obtained from PETW [48].

There are also sustainability initiatives which include increasing emphasis currently placed on conducting life cycle assessments (LCAs) to evaluate the environmental impacts of different PET recycling methods. This helps to identify areas for improvement and optimize recycling processes. Collaborative efforts between stakeholders in the value chain, including PET producers, recyclers, and consumers, are also being pursued to establish closed-loop systems that promote the collection, recycling, and utilization of PETW [21,59]. These recent advancements are aimed at making PETW recycling more efficient, sustainable, and economically viable, contributing to the transition towards a circular economy and reducing the environmental footprint of PET production and consumption.

3. Supercapacitor principles and applications

Supercapacitors (SCs) are gaining attention as useful alternatives to batteries and fuel cells in many fields like hybrid cars and portable electronic devices. This is owing to their extraordinary electrochemical characteristics, for instance, high specific power, excellent cycle stability, and a quick charge-discharge process [63–65]. In supercapacitors, energy is stored and released by ion-reversible desorption and adsorption processes at the electrode-electrolyte interface, making them effective energy storage devices [66,67]. It operates more effectively and has a higher energy density than a conventional capacitor, which has a lower energy density despite having a higher cell voltage and better specific power [63,68,69]. In contrast to regular capacitors, which store energy electrostatically in an electric field between two conducting plates, supercapacitors, store energy using electrochemical processes. Supercapacitors store electrical energy between double layers at the electrolyte-electrode interface. They have a large surface area and a small separation between plates, allowing for high capacitance [70,71]. To generate positively and negatively charged ions in an electrolyte solution, activated charcoal is applied to metal plates via porous or nanoscale materials. When a voltage is supplied to the plates, ions aggregate on their surfaces, forming an electrostatic double layer that operates as two capacitors connected in series [72,73].

Supercapacitors provide several benefits, including excellent performance, the ability to be easily coupled in series with batteries

(to provide higher voltages needed by power-demanding equipment), and the ability to produce high load currents due to their high specific power and low resistance. They are constructed in tiny, lightweight packages that make them easy to install in confined locations, and they are very reliable with higher charging rates, longer service lives, and longer cycling durations than batteries [73–75].

Although supercapacitors have some advantages, their fundamental disadvantage is that they have a lower energy density than batteries. Moreso, due to their low voltage limits and fast self-discharge rates, SCs need series connections to attain high voltage. SCs have the highest dielectric absorption when compared to other types of capacitors, and the complete energy spectrum cannot be used due to the linear discharge of voltage. This limits their ability to store large amounts of energy for long periods [73–75]. SCs are being improved to have higher energy density and meet challenges for better performance because they offer a good alternative to batteries for high-power and long-lasting applications.

The components of a supercapacitor are a porous membrane separator (that allows ions to travel between the electrodes), an electrolyte, and two electrodes shown in Fig. 1. These electrodes are responsible for the 1000 times greater capacitance of SCs compared to ordinary capacitors, although they have the same charge-discharge mechanism [64,66]. Supercapacitors' unique structure enables them to share characteristics with both electrochemical batteries and ordinary capacitors. To attain high performance and improved capacitance, SCs made of nanomaterials have larger electrode surfaces [76,77].

The electrodes are commonly made from activated carbon or carbon nanotubes, which have a high surface area and a large contact area for electrolyte ions. Supercapacitors are significant due to their exceptional properties, which make them valuable for a large range of applications [64,69]. The energy and power density are determined by the electrolyte's stability and the utilization of electroactive compounds. When evaluating the usefulness of supercapacitors in actual applications, several different criteria, including cell capacitance, voltage window, power density, impedance, time, and energy density, are taken into consideration. Alongside, safety, device stability, reduced heating, flexibility, and light weight, and some crucial features of SCs are given [33,66].

Supercapacitors have emerged as a compelling option for applications that demand high-power bursts, due to their quick energy supply and absorption capabilities. These devices can expediently release energy on demand, thanks to their faster charging and discharging speeds relative to traditional batteries [77]. Additionally, supercapacitors exhibit remarkable resilience and durability compared to batteries, withstanding hundreds of thousands to millions of charge-discharge cycles without significant deterioration. With very high charge/discharge efficiencies, they minimize energy loss during operation and optimize energy retrieval [72,73]. Furthermore, supercapacitors demonstrate impressive temperature tolerance, operating effectively across a broad range of temperatures. Their superior safety profile, without the risk of thermal runaway or explosion, sets them apart from batteries [78]. Nevertheless, sufficient voltage and current management is a prerequisite for safe operation. Supercapacitors can synergistically operate with batteries to provide an effective buffer for high-power requirements. During low-power periods, they can efficiently recharge, and during peak loads, they can quickly deliver power, enhancing overall system performance and extending battery life. Supercapacitors have diverse applications in several fields, including transportation (electric, hybrid, and regenerative braking), renewable energy systems (grid stabilization, smoothing intermittent energy sources), consumer electronics (portable devices, wearables), aerospace (emergency power backup, aerospace systems), and others [73,77,79,80].

3.1. *Types of supercapacitors*

Electrostatic double-layer capacitors (EDLCs), pseudocapacitors, and hybrid capacitors make up the three clusters of supercapacitors based on how they store charge. As shown in Fig. 2, EDLCs keep their charge by forming an electrical double layer on the electrode surface without engaging in any irreversible chemical reactions [65,81]. The performance of the EDLC can be affected by the electrical attributes of the protecting dielectric material. Each electrolyte experiences an electric field when a voltage is applied across

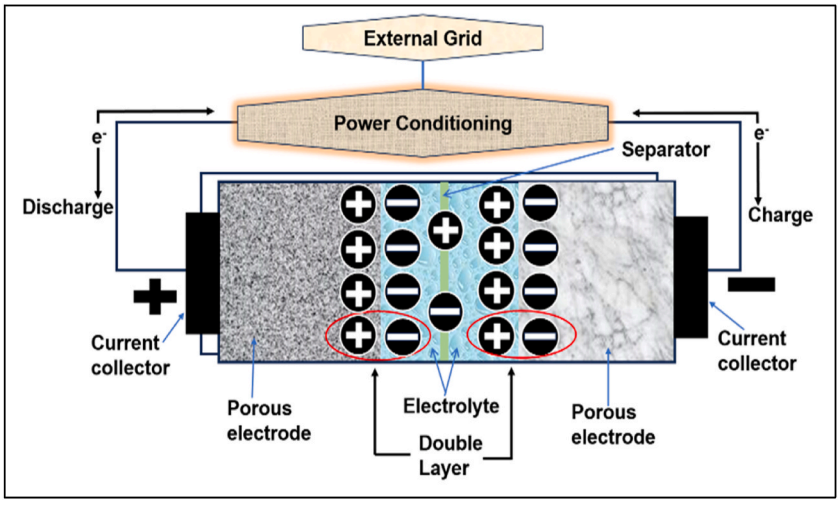

Fig. 1. Schematic diagram of a supercapacitor system.

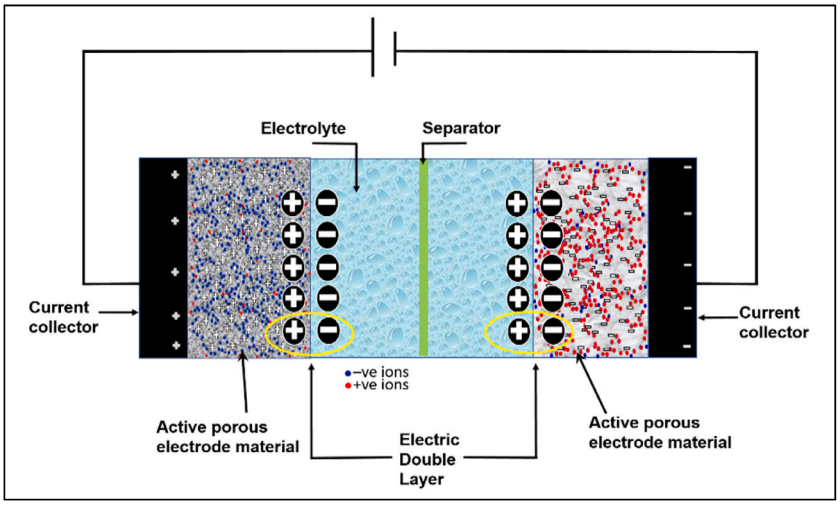

Fig. 2. Schematic representation of electric double-layer capacitors.

the terminals, resulting in its polarization. The particles accordingly navigate the dielectric to the permeable terminals, where they create inverse charges. An electric double layer is formed on each electrode as a result, increasing the surface area and decreasing the distance between them. It is crucial that the electrical properties of the insulating dielectric material can significantly impact the performance of the supercapacitor. In this manner, the choice of a suitable dielectric material is essential in amplifying the proficiency and life expectancy of the EDLC supercapacitor [65,81,82].

Pseudocapacitors, also known as faradaic supercapacitors, utilize conducting polymers, such as polyanilines, polypyrroles, polythiophenes, and metal oxides, such as MnO_2 and RuO_2, as electrode materials that are redox active. These electrodes store charge near the electrode or at the electrode surface, where charges are transferred across the metal-electrolyte interface, employing reversible faradaic reaction mechanisms [65,68,83] (see Fig. 3).

Hybrid capacitors shown in Fig. 4, are comprised of electrodes with diverse properties depending on chemical and electrical principles and feature both the EDLC and pseudo capacitor technologies. As a result, one electrode exhibits electrostatic capacitance while the other exhibits electrochemical capacitance. The benefits include a greater working voltage, larger capacitance, and a higher energy density [72,79,85].

3.2. *Factors influencing the performance of supercapacitor*

Some of the numerous factors influencing the capacitive behaviour of supercapacitors include the following [78,86,87].

i. The capacitance of the material is directly influenced by the electrode's surface area.

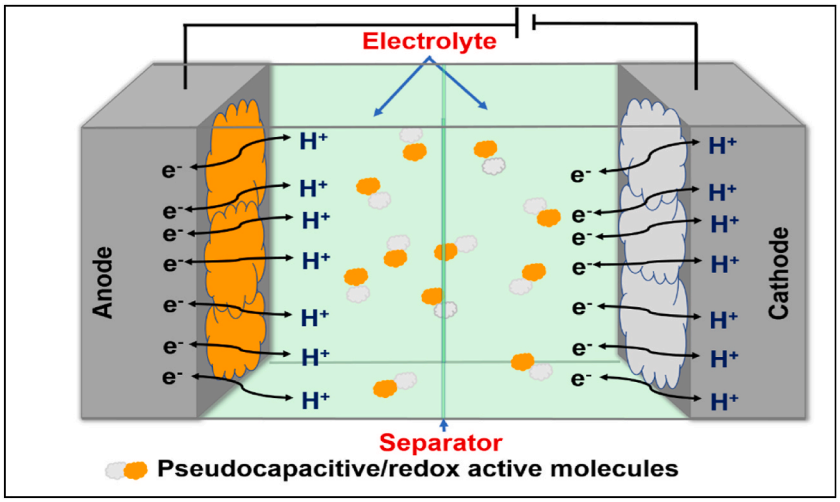

Fig. 3. *Schematic representation of pseudocapacitor. adapted from* [84].

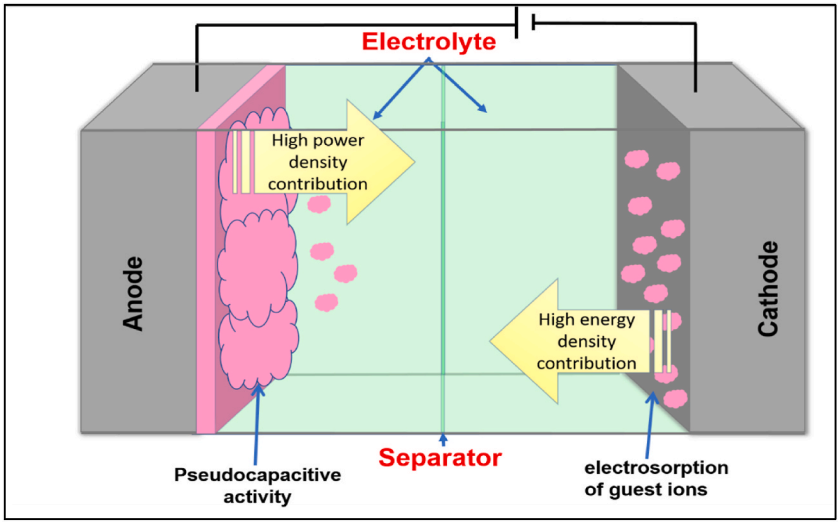

Fig. 4. Schematic representation of hybrid SC.

ii. The pore structural parameters of pore size, shape, and distribution affect the ion and charge transport mechanism, which in turn alters the electrode's capacitance.
iii. The electrochemical response of the electroactive substance is enhanced by the conductivity of the electrode and the addition of a conducting substance with binding properties.
iv. The resistance of the electrolyte and ions diffusing towards and away from the electrode are the main determinants of capacitor resistance.
v. The supercapacitor self-discharges due to current leakage caused by an unclean electrode or electrolyte.
vi. The capacitance is increased by structural flaws in the electrodes, such as vacancies, defected surfaces, and basal edges, which act as electroactive sites for the adsorption of ions. The electrode's porosity also produces excellent performance because the energy is stored on the electrode surface.
vii. Ionic liquids are more resistant to the redox process than organic and aqueous electrolytes. Aqueous electrolytes are relatively more stable than organic and ionic.
viii. The ability of materials to retain energy considerably increases by having well-defined, ideally crystalline, facets.

3.3. Common electrode materials used for supercapacitor applications

Supercapacitors' electrochemical performance is influenced by the electrolyte system, operating conditions, device configuration, and electrode materials in addition to those factors. The choice of electrode material relies on the needs of the application, such as specific capacitance, energy density, power density, cycling stability, cost concerns and environmental effects [88–90]. Several electrode materials are frequently used in supercapacitor applications, each material has its advantages and limitations.

3.3.1. Carbon-based materials (CBMs)

Carbon-based materials (such as activated carbon, carbon nanotubes, carbon fibres, carbon foams, structural graphite, graphene, etc.), are widely used in supercapacitor applications because they generally exhibit high specific capacitance due to their large surface area and porous structure, good conductivity, and electrochemical stability. Carbon materials offer high specific capacitance, good cycling stability, and relatively low cost [68,91,92]. PETWs are turned into activated carbon because it has a higher capacitance value than other classic carbon materials like graphene and carbon nanotubes in both organic and aqueous electrolytes. They can have excellent cycling stability, showing minimal degradation over numerous charge-discharge cycles, and typically exhibit good rate capability, enabling fast charge-discharge processes [77,93]. Carbon-based materials can be cost-effective compared to some other electrode materials, and the specific capacitance is not always precisely proportional to the surface area of the carbon electrode, this nonlinear relationship was deduced from different activated carbons with varied pore diameters in different electrolytes [76,92].

They have high specific capacitance, great electrical conductivity (enabling supercapacitor devices to charge and discharge quickly), good electrochemical stability, are abundant, and are easily accessible from a variety of sources. They can also be processed using scalable and affordable manufacturing processes like spray coating, screen printing, or inkjet printing. They also demonstrate good compatibility with both aqueous and organic electrolytes (allowing for a wide range of electrolyte choices in supercapacitor systems) [72,94]. Improvements to their electrode architectures, specific capacitance, and energy storage performance are all being worked on through research and development, along with the investigation of novel carbon materials and fabrication methods. To further improve the capacity for energy storage and the general effectiveness of carbon-based supercapacitors, researchers are also looking at hybrid architectures or composites [85].

3.3.2. Transition metal oxides (TMOs)

Transition metal oxides (such as RuO_2, MnO_2, NiO, IrO_2, In_2O_3, Fe_2O_3, Co_2O_3, SnO_2, V_2O_5, MoO_x, Bi_2O_3, $NiCo_2O_4$, $BiFeO_3$, etc.) have gained significant attention for their potential use in supercapacitors due to their capacity for undergoing faradaic reactions, which entail reversible redox processes (with protons that freely intercalated into the oxide lattice and out of the lattice for reduction and oxidation states respectively) [95–99]. TMOs offer high specific capacitance through redox reactions and pseudocapacitive behaviour. TMOs have a wide operating potential range, which enables supercapacitor devices to have a wider voltage window, this increases their energy storage capacity and power density. Generally speaking, they have strong electrochemical stability, allowing them to withstand repeated charge and discharge cycles without noticeably degrading their performance, hence the long cycle life and dependability [100]. TMO-based supercapacitors offer pseudocapacitance due to their redox reactions leading to higher energy storage capacity than purely double-layer capacitors [101]. They often have comparatively higher specific capacitance than carbon-based materials (which enables further charge storage beyond electrostatic double-layer capacitance) but lower than pseudocapacitive materials. Their cycling stability can vary for different transition metal oxides, with some exhibiting good stability and others showing degradation over multiple cycles. TMOs may have moderate rate capability, with the charge-discharge performance affected by their electronic and ionic conductivity, and oxidation states which coexist in the continuous range without changing the phase. TMOs can be more expensive than carbon-based materials and may have limited stability in aqueous electrolytes, restricting their use in specific environments [102–105]. TMO-based supercapacitors offer flexibility in electrolyte selection based on unique application needs because they can be used with both aqueous and non-aqueous electrolytes, as such, their performance and energy storage properties can be optimised due to this compatibility.

While there are many benefits to TMO-based supercapacitors, there are also certain issues that need to be resolved, such as low electrical conductivity, volume changes during cycling, and delayed reaction kinetics. Even so, ongoing research aims to raise their specific capacitance, boost their ability to handle high charge/discharge rates and enhance their electrochemical stability. Expanding the accessible surface area of TMOs, analysing nanostructured TMOs, and devising methods for better ion and electron transport in TMO-based electrodes are some of the research goals that should be targeted.

3.3.3. Conducting polymer-based materials (CPBMs)

Conducting polymers, also referred to as intrinsically conducting polymers (ICPs), are organic polymers that conduct electricity. These active components in supercapacitor electrodes, such as phenylene, naphthalene, anthracene, polypyrrole (PPy), polyaniline (PANI), and poly(3,4-ethylenedioxythiophene) (PEDOT), are made of aromatic rings connected by single carbon-carbon bonds [106–108]. Conducting polymers, offer pseudocapacitive behaviour and good flexibility and tunable properties. Conducting polymers exhibit relatively high specific capacitance, surpassing carbon-based materials but lower than some transition metal oxides. Cycling stability can vary for different conducting polymers, with some showing good stability and others suffering from degradation over extended cycles [109,110]. Conducting polymers generally have lower rate capability compared to carbon-based materials due to slower charge transfer kinetics. Conducting polymers offer pseudocapacitance due to redox reactions, contributing to their enhanced energy storage capacity. Conducting polymers can be solution-processable, allowing for facile electrode fabrication on various substrates. Conducting polymers can experience conductivity loss upon extended cycling and may require the use of specific electrolytes [109,111,112].

Due to their pseudocapacitive behaviour, CPs often have high specific capacitance and high energy storage capacity. They also have inherent electrical conductivity, which allows for effective charge transfer inside the electrode material and quick charge and discharge rates. They may be chemically changed and doped to adjust their properties (such as capacitance, stability, and charge storage processes), and they are compatible with both aqueous and non-aqueous electrolytes, giving flexibility in electrolyte selection based on specific application needs [109,111]. Even though conducting polymer-based supercapacitors has several benefits, issues like their low energy density in comparison to other supercapacitors and their restricted long-term stability must be resolved.

3.3.4. Metal-organic frameworks (MOFs)

MOFs are porous materials composed of metal ions or clusters coordinated with organic ligands. MOFs have drawn interest lately as the active elements in their electrodes due to their adaptable qualities, large surface areas, and porous nature (providing a large number of active sites for charge storage), which facilitates high capacitance and energy storage capacity. MOFs' tuneable porosity provides a wide range of opportunities for customising their properties (such as charge storage mechanisms, electrochemical performance, and stability) [113,114]. They have high charge mobility because of the good electronic and ionic conductivity they exhibit (facilitating efficient charge transport within the electrode material). The cycling stability of MOFs can vary widely, with some materials showing good stability and others experiencing degradation over cycles due to structural changes or solvent effects [115]. MOFs may have limited rate capability due to slow ion diffusion within their porous structure. MOFs offer the advantage of tuneable porosity, allowing for guest molecule interactions and potential pseudocapacitive behaviour. MOFs face challenges related to their stability in aqueous electrolytes and long-term durability [116–118].

3.3.5. Perovskite-based materials (PBMs)

These are a promising class of electrodes that utilize perovskite materials as active components in energy storage devices. Perovskite materials have shown promise in supercapacitor applications due to their high dielectric constant and charge carrier mobility. Due to the possession of high dielectric constants and excellent electronic conductivity, they can achieve high energy density and exhibit fast charge/discharge rates. The perovskite structures allow the tailoring of their properties to optimize the performance (capacitance, stability, and electrochemical performance) in supercapacitor applications, by varying the cation and anion

compositions, as well as their crystal structures [70,119,120].

3.3.6. Other waste-derived materials (WDMs)

Supercapacitors can benefit from various waste materials, not just PET waste. The production of activated carbon from waste materials has increased recently due to its affordability, ease of use, and perceived effectiveness in addressing the environmental problem of waste management. Waste materials such as biomass, used tyres, electronic waste, and textile waste are now viable options for the first component of activated carbon in supercapacitor performance due to the composition of various wastes. To transform these materials into appropriate electrode materials, processing usually entails multiple processes [2,4,121–127]. Their utilization provides high-performance and dependable materials for energy storage applications in addition to addressing environmental concerns.

PET electrodes are a sustainable and scalable option for supercapacitors, despite having lower capacitance than some carbon materials. Transition metal oxides have higher capacitance but lower cycling stability and are more expensive. Carbon-based supercapacitors have higher power density and cycling stability than TMOs. PET-derived electrodes are affordable and have higher cycle stability than TMOs. Conducting polymers are flexible, but carbon-based supercapacitors have better stability and lower costs. PET-based electrodes are stable and scalable, while MOF-based supercapacitors have high specific capacitance but low conductivity. Perovskite-based supercapacitors have high energy density and rapid charging, but PET and carbon-based supercapacitors are more cost-efficient and stable with better cycling.

4. Recycling PET for supercapacitor applications

Recently, researchers and academics have examined the potential for recycling waste PET for use in supercapacitor (SC) applications. The environmental impact of disposing of PET can be lessened while protecting priceless resources like petroleum by recycling used PET for supercapacitor applications [128,129]. With the growing demand for portable electronics, electric vehicles, and renewable energy sources, recycling PETW has become an economical solution to both environmental concerns and the increasing need for energy storage. PETW materials can be efficiently recycled through various methods, generally, the chemical recycling process is used mainly for supercapacitor applications [1,130,131]. The procedures used to produce electrode materials for SC application from used PET bottles are shown below in Fig. 5.

To create a homogeneous feedstock, PET materials are gathered and sorted based on their resin type and colour. During the depolymerization process, the sorted feedstock is broken down into its monomer components, namely ethylene glycol and terephthalic acid [33]. To ensure high-quality depolymerized monomers, contaminants and byproducts are removed. The clean monomers are then carbonized (heated in an oxygen-free environment) and activated (through physical or chemical processes) to create supercapacitor-compatible carbon-based electrode materials. This improves their electrochemical performance by increasing surface area and porosity [132,133]. The carbon-based components extracted from PET are combined with binders and conductive additives to increase mechanical stability and electrical conductivity [134]. The resultant slurry is then placed onto a current collector and allowed to dry to create the electrode. Finally, a supercapacitor device is assembled using the manufactured electrodes and submerged in an electrolyte solution after the electrodes have been separated by a separator. This enables ion transport and charge storage within the supercapacitor [72,134–136].

There are numerous benefits to recycling used PET for supercapacitor applications. In terms of sustainability, recycling PETW lessens the need for virgin materials, protects natural resources, and lessens the environmental damage caused by disposing of PET. Recycling PETW reduces the need for crude oil and other raw materials used to make virgin PET. For sustainable development, the preservation of non-renewable resources is essential. Generally speaking, recycling PET waste uses less energy than the entire virgin PET production cycle. PETW offers a lower-cost feedstock than conventional carbon precursors, making its use as a precursor for supercapacitor electrodes potentially economically viable [93,137–140]. The properties of the carbon-based electrode materials can be tailored throughout the recycling process by adding dopants, functional groups, or other additives, which improves the electrochemical performance [76,93,141]. Because PETW is widely accessible, recycling may be scaled up to satisfy the rising demand for

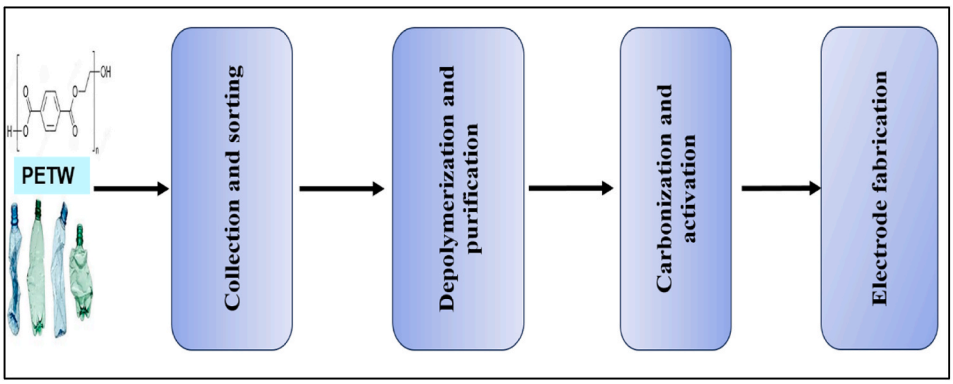

Fig. 5. PETW conversion to electrode materials.

supercapacitor applications.

4.1. Significance of PETW recycling in energy storage

Supercapacitors (SCs) stand out as an energy storage technology because of their extraordinary mix of high-power density, fast charge-discharge qualities, and long-life cycles. They effectively bridge the gap between batteries and conventional capacitors [63,66,67]. Due to their fascinating physical, chemical, and electrical properties, which have piqued the curiosity of scientists and researchers worldwide, the conversion of PETW into carbon-based electrode materials is essential for the development of high-performance supercapacitors from PETW [1,142,143]. The fact that carbon has distinct properties when compared to other elements because of its hybrid orbitals, which enable it to make numerous bonds with itself, is the primary reason that PETW is converted into carbon-based products. The hybridized bond made by get-together nuclear orbitals s and p brings about a new mixture of orbitals sp^2 and sp^3, which cause various carbon allotropes going from 0 to 3 elements of carbon [87,144].

Reusing PETW for supercapacitor applications permits us to transform waste into useable energy storage devices. This increases energy proficiency while diminishing reliance on customary energy sources that utilize petroleum derivatives. Reusing PET can be more feasible than cycling virgin materials because it eliminates the need for costly natural ingredient extraction, handling, and refining. Additionally, the production of supercapacitors may be less expensive with recycled PET [6,23]. Due to their longer lifespan, improved efficiency, and lower reliance on toxic components, supercapacitors are regarded as being better for the environment than conventional batteries. Recycling PETW for supercapacitor applications could enhance the environmental benefits of these energy storage devices and promote sustainable energy storage research and development [25,145].

Supercapacitors have several positive environmental effects that can help reduce ecological impact and promote sustainability. They provide increased energy efficiency, decreased reliance on hazardous materials and superior integration of renewable energy sources, decreased greenhouse gas emissions, waste reduction, and higher safety [146]. Since they are frequently easier to recycle than batteries, their extended operational life minimises maintenance needs and related environmental effects, helping to reduce the amount of electronic waste produced [147]. The likelihood of contaminating land and water is reduced because many supercapacitors are constructed of carbon-based materials, which are more environmentally benign, and don't use heavy metals or dangerous elements [77,92,93,137]. Rapid energy storage and release is perfect for integrating intermittent renewable energy sources into the grid, stabilising it, reducing power fluctuations, and boosting the dependability of renewable energy systems [146,148,149]. By enhancing the effectiveness of energy storage and utilization, they help reduce greenhouse gas emissions. Regenerative braking and improved energy management can lower pollutants and increase fuel efficiency in electric and hybrid vehicles [72,73]. Because of these benefits, supercapacitors are a desirable choice for environmentally friendly energy storage systems.

5. Synthesis of PET-derived electrode materials for supercapacitor electrodes

The transformation of PET (polyethene terephthalate) waste into suitable precursors for supercapacitor electrodes typically involves a multi-step process; depolymerization (which comprises collection and sorting, depolymerization and purification of PETW materials), conversion into carbon-based materials with desirable electrochemical properties (via carbonization and activation) and electrode fabrication. It is noteworthy that specific parameters, such as carbonization temperature, activation method, and electrode formulation, hold significant influence over the electrochemical performance of electrode materials derived from PET [150,151]. It is imperative to consider certain factors that may significantly impact the said performance and, thus, the effectiveness of the product. As such, depending on the desired properties of the supercapacitor electrodes and the available resources, optimization and fine-tuning of these parameters are essential to achieve the desired properties for efficient supercapacitor applications.

5.1. Carbonization and activation processes to convert PET into carbon-based materials

PET is converted into AC by a critical physical and chemical activation process in a two stages process: (i) carbonization in an N_2 environment; and (ii) activation with air, CO_2, or steam. The properties of activated carbon, which can be generated from a variety of polymers, are determined by the carbon precursors and the synthesis procedure [152]. The carbonization process involves heating the purified PET monomers in an oxygen-free environment at high temperatures (typically 400–900 °C), to break down the organic molecules and remove volatile compounds, leaving behind a carbon-rich material [133,153]. The duration of heating necessary to achieve specific properties in the final carbon material is subject to variability. Carbonized PET can yield either amorphous carbon or carbon black, both of which can be subjected to activation to enhance their surface area and porosity, ultimately improving the performance of supercapacitor electrodes.

Activation is a pyrolysis-based process that converts industrial carbonaceous materials, or industrial waste, into active materials through high-temperature exposure in an inert or low-oxygen environment [131,154]. Activation involves further treatment to introduce additional pores and increase the material's reactivity which can be achieved through physical or chemical methods. The activation process to produce activated carbon (AC) can either be physical or chemical. Physical activation which frequently follows pyrolysis involves the use of a physical agent (such as steam or CO_2, or mixes of these gases) to create pores in the carbonized PET material by exposing the carbon material to the agent at high temperatures (800–1000 °C) [155,156]. At these high temperatures, the physical agent reacts with the carbon structure, creating pores and increasing the surface area. To remove bulky volatile components, the carbon source is heated between 400 and 900 °C in an inert atmosphere during the physical activation process. An oxidising gas is then used in partial gasification at temperatures between 350 and 1000 °C. The activating agent's active oxygen first burns away the

tarry pyrolysis by-products lodged in the pores to unlock certain clogged holes. Second, a microporous structure forms as the oxidising agent burns away more reactive carbon framework regions, generating CO and CO_2 [22,154,156]. Physical activation methods are frequently employed in industrial applications due to their low production cost. However, when compared to chemical activation methods, physical activation methods yield lower activation results and less pore development. This is due to the insufficient diffusibility of the activating agent into the core regions of particles as well as microdomains of carbon materials. As a result, chemical activation methods may be more effective for achieving higher activation yields and pore development in carbon materials. The diffusibility of the activating substance and the degree of pore creation however can be increased using a novel pressurised physical activation approach [154,156].

Chemical activation is a process that entails combining a carbon source with various chemical agents, including alkalis, carbonates, chlorides, acids, or a combination thereof. The chemical activation process occurs within a temperature range of 450 °C–900 °C, and it involves impregnating the carbonized PET material with the chemical agents, followed by heating the material to the reaction temperature range [157,158]. The reaction between the carbon and the chemical agent results in an increase in the surface area and the formation of pores within the material. However, chemical activation is a process that is limited by the amount of water required to remove the contaminants produced by the process and the need to manage tainted water. Despite this limitation, chemical activation using potassium hydroxide (KOH) as an activating agent is a highly promising technique [159,160]. This is because KOH has a low activation temperature, quick activation time, higher yields, a well-defined micropore size distribution, and ultrahigh-specific surface area of the resulting porous carbons. These characteristics are crucial in charge storage and have the potential to enhance the performance of various energy storage applications. In summary, chemical activation is a promising technique for creating porous carbons with high surface areas and well-defined micropore size distributions. While the process is limited by the need to manage contaminated water, the use of KOH as an activating agent has the potential to improve energy storage applications [46,161,162].

The selection of physical and chemical activation methods, either individually or in combination, is influenced by the desired characteristics of the final carbon-based material. The resultant properties of the material are significantly impacted by the choice of activation method and specific parameters such as temperature, time, and agent concentration. Both methods elicit porosity and increase surface area, thereby enhancing the material's electrochemical properties and performance. However, chemical activation facilitates better control regarding the distribution of pore sizes.

5.2. Thermochemical conversion

The thermochemical conversion of solid polymer waste into activated carbon is an effective technique with numerous benefits. By breaking down polymeric waste into low-molecular-weight compounds that slowly evaporate when heated in the air at 360 °C, this method boasts a higher conversion rate, larger surface area, and complete conversion of organic components into carbon-based products [67,163,164]. These advantages make it an environmentally friendly solution for the treatment of waste materials. The carbonized and activated PET can be further processed and utilized as a precursor for supercapacitor electrodes, or in other applications that require high surface area, electrical conductivity, and electrochemical performance of carbon-based materials [75,165]. Various methods can be used to improve the electrochemical performance of activated carbons, including ultrasonic radiation treatment (to alter the Fermi level position), an oxidation process (to modify the surface), the incorporation of heteroatoms (such as S, O, and N), or the formation of a composite electrode by incorporating polymers into the carbon substrate [72,79]. Overall, the conversion of solid polymer waste into activated carbon through thermochemical means is a well-suited technique for businesses and organizations looking to improve their environmental impact, while also creating valuable products.

5.3. Electrode fabrication

The PET-derived carbon-based materials are then processed into electrode structures suitable for supercapacitors by mixing with binders, to improve mechanical stability and electrical conductivity (often termed mixing and binder addition) [134]. This mixture is then coated onto a current collector, such as a metal foil or mesh, using techniques like doctor-blading, dip-coating, or spray-coating. This forms a uniform and well-adhered electrode layer on the collector. The coated electrode is dried to remove any solvent or moisture, to form the electrode, which may undergo compression to improve its density and adhesion to the current collector [72,92].

5.4. Electrode testing and assembly of supercapacitor

The fabricated electrode is characterized using various techniques, such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and electrochemical measurements, to evaluate its morphological, structural, and electrochemical properties. Finally, the electrodes are assembled into a supercapacitor device by sandwiching them between separators (which allow ion transport) and immersing them in an electrolyte solution. The electrolyte facilitates charge storage and ion exchange within the supercapacitor [72,92,166].

5.5. Doping and functionalization strategies to enhance electrochemical performance

Doping and functionalization techniques are commonly utilized to enhance the electrochemical performance of carbon-based materials employed in supercapacitor electrodes. These techniques entail the incorporation of foreign elements or functional groups into the carbon structure to modify its properties. Either strategy or a combination of both can be employed to tailor the

electrochemical properties of carbon-based materials for specific supercapacitor applications [87]. The selection of a strategy is reliant on the desired performance characteristics and the specific requirements of the application.

Doping refers to the intentional introduction of foreign atoms or ions (like nitrogen (N), phosphorus (P), sulfur (S), and various transition metals) into the carbon lattice, to alter the electronic structure, conductivity, and surface chemistry of the carbon material [167,168]. Nitrogen doping introduces nitrogen atoms into the carbon lattice, leading to enhanced pseudocapacitance and improved electrochemical performance, because nitrogen atoms can modify the electronic properties of carbon, increase the surface area, and provide additional active sites for charge storage [169,170]. Phosphorus and sulfur doping can also improve the electrochemical performance of carbon materials, however, while phosphorus doping increases the conductivity and capacitance, sulfur doping generally enhances the capacitance and stability of the carbon material [171,172]. Doping of carbon materials with transition metals, such as iron (Fe), cobalt (Co), or manganese (Mn), can significantly enhance their electrochemical properties. The transition metals introduce redox-active sites, promote charge transfer kinetics, and increase the specific capacitance of the carbon material [102].

Functionalization involves attaching functional groups or molecules to the carbon surface, in a bid to modify the surface chemistry, introduce new functionalities, and enhance the electrochemical properties of the material. Introducing oxygen-containing functional groups such as hydroxyl (-OH), carbonyl (C=O), or carboxyl (-COOH) groups, can improve the wettability, increase the active surface area, and enhance the electrochemical performance of carbon materials [173,174]. Introducing heteroatoms (heteroatom functionalization), such as oxygen (O), nitrogen (N), or sulfur (S), as functional groups can alter the electronic properties and surface chemistry of carbon materials. Heteroatom functionalization enhances the pseudocapacitive behaviour, increases the charge storage capacity, and improves the stability of supercapacitor electrodes [87,174,175].

5.6. Electrode binders

In an electrode system, while the active materials have the greatest influence on supercapacitor capacitance, the binder materials play a vital role in electrode manufacturing, providing mechanical support and flexibility. Salleh et al. [134] discussed the variety of binders and their unique characteristics, which have a significant impact on supercapacitor electrode performance in a recent review. Polymer binders are crucial for improving supercapacitor electrodes, as they enhance performance and flexibility by acting as a glue between the active materials and current collectors, preserving the mechanical integrity of the electrode [134].

Surface coating of the carbon material with conductive polymers, such as polyaniline (PANI), polypyrrole (PPy), or poly(3,4-ethylenedioxythiophene) (PEDOT), can also be used to enhance the electrochemical performance of the material [112,176]. This provides additional redox-active sites, thereby, increasing the electrical conductivity, and improving the stability of the electrode material [111,135].

5.7. Exploration of novel approaches for synthesizing PET-derived electrode materials

The exploration of novel approaches for synthesizing PET-derived electrode materials is an active area of research aimed at developing sustainable and efficient energy storage solutions. A few emerging techniques have shown promising results including hydrothermal carbonization, solvothermal conversion, microwave-assisted pyrolysis, and electrochemical conversion [177–179]. These techniques are still under investigation, and their feasibility and scalability for large-scale PETW conversion into electrode materials are subjects of ongoing research. Additionally, the specific parameters and conditions for each technique may vary depending on the desired properties of the final electrode material.

Hydrothermal carbonization (HTC) is a technique that involves the carbonization of biomass or organic waste materials at moderate temperatures between 150 and 400 °C and high-pressure conditions in the presence of water [179,180]. Hydrothermal carbonization techniques offer greater yields and more adjustable shape and porosity of carbon products as compared to pyrolysis and chemical activation. However, this method needs time-consuming post-processing to produce the desired outcome. This approach has been explored for converting PETW into carbonaceous materials. The process promotes the polymer decomposition and carbonization of PET, resulting in the formation of carbon-rich materials with enhanced surface area and porosity [179,181,182]. The HTC process can be further modified by adding catalysts or dopants to tailor the properties of the resulting carbon materials.

The creation of activated carbon-based materials sometimes requires a combination of soft and hard templates or a blend of both in template-based assisted carbonization [183]. The hard template-based method is a useful technique for producing macroporous structures with the aid of hard particles such as zeolites, metal-organic frameworks, mesoporous silicas, and clay materials acting as a sacrificial structure controller. This methodology enables the fabrication of highly organized structures, and the process is advantageous in producing carbonaceous materials for use in supercapacitor applications from industrial waste. However, the technique's effectiveness is limited by the structure collapse, instability, and pore blockage that occur during template etching or in the case of a soft template [181,184]. In this method, the voids created by colloidal particles are filled with fluid-like carbon raw materials that permeate the templates and later solidify. Upon conversion of the solid fillers into a solid carbon framework in an inert atmosphere, the sacrificial templates around the air holes left in the starting positions of the solid particles are subsequently eliminated by the pyrolysis process or by chemical etching [114,165,181]. To create an ordered porous carbon structure doped with heteroatoms, a heteroatom-rich chemical is made to interact with the precursor. Subsequently, KOH activation is done to produce a hierarchically porous carbon structure [152,160].

The soft template-based technique is also a desirable strategy because it offers desirable advantages like the capacity to create carbon-based materials with various morphologies in less demanding experimental conditions, using block copolymers and organic molecules [185]. Structure-directing agents and carbon material precursors in solution are assembled during the inter-assembly of

organics to create mesoporous carbon materials with the desired size. When opposed to hard templates, soft template systems are less stable. Additionally, the heteroatom-rich compound can be used to create the ordered porous carbonaceous material that is doped for use as a supercapacitor electrode [181,186]. An effective strategy for achieving high electrochemical performance in supercapacitors will involve the integration of soft and hard template methods to produce hierarchical porous carbon-based materials with mesopores and macropores. Such templates typically comprise triblock copolymer micelles and hard particles, where soft templates fill the voids of the hard templates during preparation. Notably, the macropore-based ordered porous carbon supercapacitor electrode excels in facilitating ion transport and electrolyte access, thereby enhancing the loading and dispersion of electroactive components [142,169]. The use of macropore-based materials could be a promising avenue for developing high-performance supercapacitors.

Ionic liquids are the starting point for the ionothermal carbonization process, which produces high-quality carbon functional materials from polymers with large specific surface areas and pore volumes [187]. The ionothermal method provides some advantages over traditional carbonization techniques, including the flexibility to modify the composition and processing conditions of the ionic liquid to alter the carbon structure and properties. It also exhibits substantially superior electrochemical performance than ordinary carbon materials and enables the straightforward manipulation of the porosity of synthetic porous carbon materials by varying the sizes of anions without the need for templates or additives [181,188,189]. This strategy may be effective in addressing the issue of pore structure collapse during carbonization.

By functionally inducing in-situ doping, surface modification, and structural adjustment during additive-assisted carbonization, it is possible to change the size and surface properties of carbon materials [181]. Continuous carbonization, thermal stabilization, and RF resin penetration of the carbon material are all part of this process to maximise particular electrical conductivity and cycling ability [153,190]. By exposing polymer films to an infrared CO_2 laser under the right circumstances, a technology known as CO_2 laser carbonization can be used to convert them into porous graphene or laser-induced graphene (LIG) in a two-step process [181,191–193].

Microwave-assisted pyrolysis is a process that uses microwave radiation to rapidly heat the starting material and encourage its thermal decomposition [48,178]. PETW can be transformed into carbon-based materials through microwave-assisted pyrolysis. The pyrolysis process can be precisely controlled thanks to the rapid and effective heating provided by microwaves, which results in the production of carbon materials with the desired properties. This approach has the potential for high return and energy productivity [48,178,194].

Solvothermal conversion uses high temperatures, high pressures, and the presence of solvents to convert starting materials into the required products [195]. PETW can be exposed to solvothermal treatment utilizing solvents like ethylene glycol or other natural mixtures. The interaction advances the depolymerization of PET and ensuing carbonization, prompting the development of carbon-based materials appropriate for supercapacitor electrodes [177,195]. PETW can also be converted into electrode materials via electrochemical techniques, with the PET generally electrolyzed in a suitable electrolyte solution as part of the process. The electrochemical cycles convert the PETW into carbonaceous materials, which can then be further processed and used as cathode materials for supercapacitors [196,197]. Electrochemical conversion offers the upside of exact command over the response conditions and the potential for versatile combination.

5.8. Difficulties reported during the synthesis of PET-derived electrode materials

The overall performance of the supercapacitor device relies on the properties of PETW, which can vary depending on its source and previous use, leading to inconsistencies in the performance of the electrode materials. This is often due to the presence of pollutants and impurities in the PETW, which can diminish the quality of the final electrode material [1,142,198,199]. As such it can be difficult to achieve a consistent electrochemical performance in batches of materials made from PETW. By improving the methods for sorting and cleaning to lower contamination and variability in PETW feedstock, this can be avoided. Creating supercapacitor electrodes with the necessary high surface area and ideal pore size distribution can be challenging. The activation process often involves chemicals, leading to complexity and environmental concerns for proper handling and disposal. However, the processes of breakdown and activation can be energy-intensive and may counteract some of the environmental advantages of utilizing waste PET [93,155,200].

Furthermore, obtaining the desired qualities (such as high capacitance, low resistance, and long cycle life) for supercapacitors using PETW-derived electrode materials necessitates thorough optimization, and precise control over temperature, atmosphere, and timing. Utilizing eco-friendly activation techniques and reducing the use of dangerous chemicals as well as creating and applying methods for PET conversion that are based on renewable energy sources and energy efficiency will boost sustainable chemical use in a circular economy [180,201]. Moreso, high processing costs can hinder widespread implementation, especially when transitioning from laboratory to industrial-scale production. Offering financial rewards and assistance to encourage the expansion of sustainable practices can increase their economic feasibility. Moreso, using innovative materials derived from recycled plastic may face resistance due to concerns about their durability, performance, and long-term stability. Putting in place guidelines and quality assurance procedures to guarantee PETW-derived materials operate safely and consistently, as well as fostering market acceptability and demand by raising awareness can boost acceptance of sustainable materials and technologies for a circular economy [9,18,56]. Therefore, to create electrode materials from recycled PET, these challenges must be addressed to ensure the process is effective, profitable, and of high quality. Achieving this requires ongoing research and development with the aid of technological advancements and a greater emphasis on sustainable materials.

6. Performance of PET-derived supercapacitors

6.1. Electrochemical performance of PET-derived supercapacitors

The electrochemical performance of PET-derived SCs relies upon a few variables, including the properties of the PET-derived cathode materials, the electrolyte utilized, and the gadget setup. Specific capacitance, rate capability, cycling stability, electrochemical impedance, energy density, power density, and electrolyte compatibility are some important factors that also affect the electrochemical performance [202–204]. Specific capacitance, cycling stability, rate capability, and impedance analysis are critical considerations when evaluating the electrochemical performance of supercapacitor electrode materials. These limits provide crucial information about the materials' long-term stability, charge-move energy, charge-storing limit, and charge-release behaviour [68,91,205]. Choosing the best electrode materials for various supercapacitor applications can be made easier with a better understanding of these evaluations.

The charge storage limit per unit mass or unit surface region of the cathode material is estimated by the specific capacitance. Since it shows whether a material can store electrical energy, it is a pivotal variable in deciding how successful supercapacitors are at putting away energy. Different electrochemical strategies, for example, cyclic voltammetry (CV) or galvanostatic charge-release (GCD) tests, can be utilized to work out the specific capacitance. High-explicit capacitance electrode materials produced using PET can store more charge and convey more energy [174,175,206]. The charge stored can be determined from equation (1), while the capacitance is influenced by the permittivity of the dielectric medium (€), the spacing between the conductors (d), and the active area (A) of the capacitor conductor ((as estimated by the number of plates) [33]:

$$Q = CV \tag{1}$$

Where: Q is the charge (C), C is the capacitance and V is the supplied voltage (v)

$$C = \frac{€A}{d} \tag{2}$$

The term "fast charge-discharge rates" refers to a supercapacitor's rate capability, which evaluates an electrode material's performance in high-current density environments. It is essential for applications that require rapid energy supply and storage. Rate capability can be computed by examining the variations in the material's specific capacitance and voltage responsiveness at different current densities. At large current densities, a material with good rate capacity shows little loss in capacitance and voltage efficiency. High electrical conductivity and superior ion diffusion qualities of PET-derived electrode materials allow for effective charge transfer and ion transport, which improves the supercapacitor's performance at high current densities [71,135,205].

The cycling stability of a supercapacitor reflects its ability to maintain consistent electrochemical performance over multiple charge-discharge cycles without significant degradation. It is evaluated by subjecting the electrode to repeated cycles of charging and discharging and monitoring any changes in specific capacitance or voltage profiles [181]. High cycling stability indicates the material's durability and reliability over extended usage. PET-derived electrode materials with good structural stability and resistance to degradation can exhibit excellent cycling stability, ensuring the long-term durability and reliability of the supercapacitor [179].

The electrochemical impedance of a supercapacitor is characterized by parameters such as equivalent series resistance (ESR), charge transfer resistance, and double-layer capacitance, which can be determined with the help of impedance analysis. Impedance analysis, typically performed using electrochemical impedance spectroscopy (EIS), provides insights into the electrical properties and charge transfer kinetics of an electrode-electrolyte interface [180,182]. EIS involves applying a small AC signal to the electrode and measuring the resulting impedance response. Lower values of ESR and charge transfer resistance indicate better conductivity and more efficient charge transfer kinetics, leading to improved electrochemical performance. Impedance analysis also enables the identification of different components contributing to the total impedance, such as solution resistance, electrode-electrolyte interface resistance, and diffusion processes [207,208]. By fitting the impedance data to appropriate equivalent circuit models, the individual contributions of these components can be quantified and analysed.

The two main measures for supercapacitors are energy density and power density. Power density quantifies the speed at which energy may be provided or retrieved, whereas energy density refers to the quantity of energy stored per unit mass or volume of the supercapacitor [63,73,209]. PET-derived electrode materials with good ion diffusion properties, low equivalent series resistance, and high specific capacitance will allow higher energy and power densities. The choice of electrolyte also plays a significant role in the electrochemical performance of PET-derived supercapacitors. The electrolyte should have good compatibility with the electrode materials, provide sufficient ionic conductivity, and enable stable electrochemical reactions. Commonly used electrolytes include aqueous solutions (such as alkaline or acidic solutions) or organic electrolytes (such as acetonitrile or propylene carbonate) with suitable additives [175,186,210].

To enhance the electrochemical performance of PET-derived supercapacitors, various strategies can be employed, such as doping or functionalizing the carbon-based electrode materials, optimizing the electrode structure, exploring novel electrolyte systems, and engineering the device configuration. These strategies aim to improve specific capacitance, rate capability, cycling stability, and overall energy storage performance. Extensive research and development efforts are ongoing to explore new materials and techniques to enhance the electrochemical performance of PET-derived supercapacitors and advance their practical applications.

6.2. Evaluation of the electrochemical properties of PET-derived electrode materials

The electrochemical properties of PET-derived electrode materials can be evaluated through several characterization techniques and electrochemical measurements. The evaluation of electrochemical properties is typically performed in conjunction with other material characterization techniques, such as X-ray diffraction (XRD), Raman spectroscopy, and elemental analysis. This is to gain a comprehensive understanding of the PET-derived electrode materials' composition, structure, and electrochemical behaviour. The most used methods for evaluating the electrochemical properties include cyclic voltammetry, galvanostatic charge-discharge (GCD) and electrochemical impedance spectroscopy (EIS) measurements, specific capacitance, electrochemical stability, as well as surface morphology and structure analysis [82,161].

Cyclic voltammetry (CV) is a typical technique for assessing the electrochemical behaviour of supercapacitor terminals. It is based on a quick voltage scan technology that reverses the direction of the scan across a chosen voltage range when a potential is applied to the working electrode in both forward and reverse orientations. The resulting current can be measured as a single cycle or several cycles and the electrode material's soundness, redox conduct, and capacitance are estimated. The state of the CV curves can uncover the presence of faradaic responses and twofold layer capacitance [207,211]. The voltage response of the supercapacitor electrode is tracked over time during GCD tests with a constant current. Significant elements like explicit capacitance, energy thickness, power thickness, and rate ability can be determined by estimating the release curve. GCD estimations additionally shed light on the charge-storing processes and the capacitive way of behaviour of the electrode [82,176,212].

The specific capacitance of PET-derived electrode materials can be determined from the CV or GCD estimations utilizing the accompanying equation [82,212,213]:

$$\text{Specific Capacitance (Csp)} = \int (\text{I dV}) \Big/ (2\pi\nu\text{m}\Delta\text{Vm}) \tag{3}$$

where I is the current, V is the potential, νm is the scan rate, and ΔVm is the potential window.

The charge transfer kinetics and electrical characteristics of supercapacitor electrodes can be studied well with EIS. It entails passing a weak AC signal across the electrode and determining the response's impedance. The electrode-electrolyte interface's capacitance, charge transfer resistance, and equivalent series resistance (ESR) can all be unveiled by EIS. The various elements contributing to the total impedance can be determined by fitting the impedance data to relevant equivalent circuit models [207]. The electrochemical stability of PET-derived electrode materials can be evaluated by performing long-term cycling tests or voltage-holding tests. Voltage holding tests entail providing a steady voltage to the electrode and tracking the stability of the potential over an extended period, whereas continuous cycle testing by periodically charging and discharging the supercapacitor electrode will evaluate its stability and degradation over time [90,112,204].

Surface morphology and structure analysis such as SEM, FESEM, XPS, TEM, and BET, etc., can be used to examine the morphology and microstructure of PET-derived electrode materials [214,215]. These techniques provide information about the porosity, particle size, and distribution of the carbon-based material, which can influence the electrochemical performance.

6.3. Experimental results highlighting the performance of PET-derived supercapacitors

PET-derived electrode materials have demonstrated potential in supercapacitor applications because of their composition rich in carbon and their potential for high specific surface area. To simultaneously address the recycling and energy storage challenges, several authors have shown how to employ PETW to create high-performance, low-cost carbons with better qualities for SCs (shown in Table 1). To turn PET into carbon nanomaterials (CNMs), Kigozi et al. [129] used a thermal-hydrothermal method. The CNMs, when

Table 1
Summary of some experimental works on the use of PETW for SC application.

PETW-derived Material	specific capacitance (F/g)	energy density (Wh/kg)	power density (W/kg)	Ref
PTNANO	277.8/457.05 (cv)	34.83	999.9	[129]
ACs	106-197 (aq. elect.) 69-98 (apr. medium)	3–4	2635	[216]
PCS-MnO_2 composites	210.5	–	–	[133]
MMPC	191.4	–	–	[217]
PAC/MoS_2–C	183/241 (CV) 214/288 CGCD)	30/36	364/469	[218]
NMC	230 (CV)/295 (GCD)	–	–	[136]
Cu-MOF	104.8	18.2	825	[115]
NiOx@NPC nanocomposite	581.30/291 (in device)	–	–	[128]
$NiCo_2O_4$@nitrogen-doped carbon NCs	890 (CV)/913 (GCD)	–	–	[219]
HPC	413	25		[140]
AC-K	325	–	91.86	[131]
AC	36.2	–	–	[130]
ACs	220	36.9	61.1	[150]
PCNS	169,135,121	30.6	–	[138]
3D N-doped graphene nanosheets	405	68.1	558.5	[220]

tested for supercapacitor performance with a symmetric fabrication, revealed a specific capacitance of 277.8 F/g, an energy density of 34.83 Wh/kg, and a power density of 999.9 W/kg. After 10000 cycles, the SC device demonstrated great cycle stability and high capacitance retention of 96.8 % with a current density of 1.5 A/g. Domingo-Garcia et al. [216] compared PET-based activated carbons (Acs) made for use as supercapacitors using various synthesis techniques. The PET-derived activated carbons exhibit specific capacitances at low current densities between 106 and 197 F/g in aqueous electrolyte and from 69 to 98 F/g in an aprotic medium, following the general patterns for extremely porous carbons. High performance has additionally been attained at high current densities, thanks in part to specific oxygen surface functions that facilitated quick redox reactions (pseudo-capacitance).

Mu et al. [133] researched carbonising PETW, to create three-dimensional (3D) porous carbon nanosheets (PCS) that could be combined with MnO_2 nanoflakes to create PCS-MnO_2 composites. The final composite displayed a 210.5 F/g specific capacitance. It also had outstanding cycle stability. PETW was also successfully transformed into 3D porous carbon by Chen et al. [217], using MgO-templated pyrolysis with chemical activation, which produced carbon with a high capacitance of 191.4 F/g and excellent rate capability (86.3 % retention from 0.5 to 10 A/g) for supercapacitors. PET-derived activated carbon prepared via carbonization and subsequent activation under various conditions has performed well electrochemically as a supercapacitor active material. The material was proven to have high retention rates at high charge-discharge rates and good durability according to research by Jung et al. [91]. Sangeetha et al.'s [218] usage of PETW as an activated carbon source to synthesise carbon-doped MoS_2, greatly increased the power density. They created supercapacitor electrodes that were symmetric and hybrid and that produced a greater energy density of 36 Wh/Kg and a higher power density of 469 W/kg. The porosity network of the synthetic material and doping was attributed to this performance.

Ubaidullah et al. [136] also studied supercapacitor electrodes made of PET-based carbonaceous porous materials (such as activated carbon, nanosheets and MOFs). Using the MOF-5 fabrication technique, they created high surface area nitrogen-doped mesoporous carbons that exhibited improved specific capacitance of 230 F/g and 295 F/g when tested using galvanostatic charge-discharge (GCD) at 0.5 A/g and cyclic voltammetry (CV) at 5 mV/s, respectively and evaluated it in super-capacitor assembly. Additionally, the GCD stability test revealed a retention rate of 98 % after running 400 segments. Using a hydrothermal method, Dubey et al. [115] created MOFs from PETW and electrochemically evaluated them. Among them, Cu-MOF (104.8 F/g at 0.5 A/g) outperformed its rivals in terms of capacitance, diffusion contribution (78.4 %) and good cycle stability. Additionally, Cu-MOF solid-state symmetrical supercapacitor devices outperformed the competition with an energy density of 18.2 Wh/kg at a power density of 825 W/kg and a cyclic stability of 87 % after 10,000 charge-discharge cycles. This is likely because it has a larger surface area and a greater contribution from diffusion than its competitors.

Al-Enizi et al. [128] were able to create PET-derived MOFs based on NiO_x nanoparticles embellished with porous carbon that contained nitrogen (NiOx@NPC nanocomposite). The nitrogenous porous carbon improved the charge relocation process for better supercapacitor device performance in addition to improving electrical conductivity and stability, demonstrating an excellent 581.30 F/g specific capacitance. Furthermore, the manufactured symmetric supercapacitor device showed a specific capacitance of 291 F/g, with outstanding cyclic stability. Bimetallic $NiCo_2O_4$@nitrogen-doped carbon nanocomposites with high specific capacitance of 890 F/g by CV and 913 F/g by GCD were created by Alhokbany et al. [219] using waste PET. These materials displayed good electrochemical performance, excellent retention capacity (99 %) and good cyclic stability.

Liu et al. [140] looked into the development of hierarchical porous carbon structures from PET using the co-etching effect of sp2/sp3 hybridized carbons, which were then activated to produce hierarchical porosity. While the conventional microporous carbon exhibits a low capacitance of 142 F/g, the derived Hierarchical porous carbons (HPCs) based electrode reaches an exceptional capacitance of 413 F/g. The symmetric supercapacitor created had a high energy density of 25 Wh/kg.

PETW was converted into carbon material by Zhang et al. [131] via pressure pyrolysis and post-activation. With a low ESR and strong cyclic stability, the activated pyrolytic carbon hierarchical porous structure demonstrated an exceptional specific capacitance of 325 F/g. Mirjalili and colleagues also produced electrochemical active carbon material from PETW with enhanced pseudo capacitance using an electrospinning fibre production method [130]. Dedek et al. [150] successfully converted PETW into activated carbons with competitive electrochemical performance, showing 220 F/g specific capacitance, 61.1 Wh/kg and 36.9 kW/kg energy and power densities, and excellent cycling stability.

The individual synthesis procedures, activation strategies, and device designs employed in various research can have an impact on the performance of supercapacitors made from PETW, as shown in the reported studies. To further improve the electrochemical performance of PETW-derived SCs, research should look at optimizing these synthesis procedures, study innovative electrode designs, and investigate advanced doping or functionalization techniques.

7. Challenges and future directions

PETW reuse must be implemented as a workable method as part of naturally conscious practices. Eco-friendly combination strategies, which ensure proper removal or recycling methods, should be the focus in every scenario. With the continual advances in material combination, device designing, and framework reconciliation, supercapacitors produced using PETW hold the possibility to act as eco-accommodating energy-storing choices for many applications. Further research should address concerns related to adaptability, energy density, cycling stability, ecological effect, and adding novel materials and functions to further advance the performance of PET-derived supercapacitors. To guarantee the commercial feasibility of these supercapacitors, procedures that transform PET waste into high-performance, reasonably priced electrode materials are necessary. However, it is important to remember that PET-derived supercapacitors have a lower energy density when compared to conventional energy-storing techniques like batteries.

The use of polyethene terephthalate waste (PETW) as a material for supercapacitor applications is hampered by some intrinsic

issues. Impurity content, heterogeneous composition, decreased energy density, limited control over structure and porosity, scalability and cost-effectiveness, stability and degradation, environmental impact, and compatibility with current systems are a few of these. Moreover, effective source segregation techniques can be applied at the waste generation site to minimize PETW contaminants, through advanced separation to ensure feedstock homogeneity. This should be accompanied by advanced chemical treatments, purification methods and real-time process monitoring techniques. The collaboration between academia, industry, and government can also foster creative and ecologically beneficial recycling methods.

Hybrid systems and composite materials are gaining attention as promising methods to improve the performance of supercapacitors and should be investigated further as they can yield both economic and environmental benefits. These systems provide a flexible platform to optimize supercapacitor performance for different applications by adjusting composition, structure, and interface properties. They provide enhanced energy storage capacity, by combining electrostatic and pseudocapacitive properties of different materials to provide high specific capacitance and high-rate capability, resulting in improved overall performance. The materials can be functionalized, doped, or have their composition changed to improve their electrochemical properties and increase their attractiveness for particular uses. By closely analysing the interactions between various energy storage techniques and materials, high-performance PETW supercapacitors can be produced.

There are several crucial aspects to consider when evaluating the viability of recovering PET waste for use in supercapacitors. The competitive environment, long-term partnership and finance, material quality and consistency, energy and resource efficiency, market demand and application possibilities, cost-effectiveness, scalability, and regulatory and environmental factors are some of these. It is essential to compare the cost of the recycling process to the value of the commodities generated to assess whether recycling PET waste is economically feasible through life-circle assessments. Recycling PET waste for use in supercapacitors necessitates cooperation with industry partners, process optimization, quality control, and a thorough grasp of market dynamics. Furthermore, the use of waste materials can aid in diversifying the supply chain and reducing the dependence on rare or expensive raw materials, ultimately decreasing the overall manufacturing costs of supercapacitors. To realize their maximum economic potential, businesses must strike a balance between cost-effectiveness, material quality, market demand, and environmental concerns. A circular economy approach can then be realized through continuous innovation, stakeholder engagement, and government involvement.

All things considered, PET-derived supercapacitors have a great deal of promise as environmentally friendly energy storage options, but there are currently a lot of issues that need to be watched out for. These challenges incorporate adaptability, energy density, cyclic stability, and the synchronisation of innovative materials and functionalities. Furthermore, future research should concentrate on innovative electrode materials, device designs, and electrolyte framework enhancement that will address electrode deterioration, structural stability, and electrolyte compatibility. Research and developmental efforts in material synthesis and modification, process optimization, and system integration, utilizing cutting-edge techniques must continue to meet these difficulties.

8. Implications of the review and opportunities

This review explores the potential of using PETW recycling for supercapacitor applications, and considerable promise exists for industrial applications, policy development, and commercialization The research has the potential to bring about revolutionary improvements across various industries by addressing environmental concerns and providing financial benefits. Using PETW-derived materials in supercapacitors has the potential to improve overall performance and efficiency, reduce emissions, and increase energy storage capacity. These improvements are crucial for renewable energy systems, electric and hybrid vehicles, regenerative braking systems, and auxiliary power sources. The use of PETW in supercapacitors could also lead to improved lifespan and performance in consumer electronics such as wearables, computers, smartphones, and power backup systems. Additionally, PETW supercapacitors can contribute to efficient energy management and peak load handling in industrial machines.

The competitiveness of PETW-based products on the market and their prospects for commercialization can be increased by developing cost-effective recycling processes and supercapacitor production techniques. Demonstrating the feasibility of PETW recycling and supercapacitor production can attract financing and foster industry acceptance. Growing consumer and governmental demand for sustainable products may drive the market for PETW-based supercapacitors and other recycled items. PETW recycling solutions can help businesses meet their CSR commitments while also enhancing their sustainability reputations. Applications for PETW may become more appealing and practical as long as recycling methods and supercapacitor performance advance technologically. Productive integration of PETW-derived materials into existing production processes can facilitate smoother market penetration and commercialization.

Governments can provide financial incentives and subsidies to companies that invest in PETW (Polyethylene Terephthalate Waste) recycling technologies and applications. They can also enforce strict regulations on the management of plastic waste to ensure appropriate gathering, sorting, and recycling of PETW. Additionally, increasing funding for PETW recycling research and development, and its application in other high-tech industries, such as energy storage, is important. Encouraging collaborations between corporations, academic institutions, and public and private organizations can further the development and commercialization of PETW recycling technologies. Initiatives to educate the corporate community and the general public about the financial and environmental benefits of recycling PETW are essential. Furthermore, introducing regulations to influence consumer behaviour to promote recycling and support products made from recycled materials would be beneficial.

9. Conclusion

After reviewing PETW recycling for supercapacitor applications and a summary of the major discoveries and developments, we

conclude that the reuse of PETW is a successful technique for controlling resources and getting electrode materials for supercapacitors in a practical way. The utilization of waste PET to create sustainable supercapacitors provides an exceptional opportunity to address both waste management and sustainable energy storage in a simultaneous and mutually beneficial fashion. PET reusing additionally decreases the volume of delivered waste and limits the ecological effect of its removal. The utilization of reused PET for supercapacitor electrodes is a financially savvy choice since it takes out the requirement for unrefined substance extraction and handling. PET supercapacitors are a strong contender for real-world applications because studies have shown that they can provide reasonable specific capacitance and energy storage capacities. The review outlines future research paths and challenges, new ideas for improving the performance of PET-based supercapacitors, and areas that require additional investigation. The general evaluation underlines the potential for reusing waste PET for supercapacitor applications, featuring its benefits concerning asset preservation, natural supportability, energy productivity, and cost viability. The development of eco-friendly supercapacitors using recycled PET has the potential to significantly contribute to a landscape of energy storage that is both sustainable and mindful of the environment. Additionally, PETW recycling is feasible and scalable for large-scale production, and its worldwide availability makes it a viable source of electrode materials. In any case, with persistent advances in PET reusing, innovation and supercapacitor improvement, there is huge potential for PETW in sustainable supercapacitor advancement.

To fully realize the wider environmental preservation, energy efficiency, and sustainable future benefits this field can provide, more research and development is necessary. Investing in this area can be a significant step towards achieving our goals of a greener and more sustainable future. Continued research and development in this field are of the utmost importance as the world increasingly shifts toward renewable energy sources, and effective and sustainable energy storage technologies become increasingly paramount. Additionally, it fosters a circular economy by emphasizing the importance of recycling and reusing waste materials, reducing waste output, and supporting long-term sustainability. In Conclusion, this review aims to encourage researchers, engineers, and policymakers to invest in innovative solutions for PETW management while providing a comprehensive review of PETW recycling for supercapacitor applications. By adopting this approach, we can move towards a more sustainable future while contributing to the creation of effective and sustainable energy storage devices.

Data availability statement

The authors declare that all data associated with our study has been referenced in the manuscript.

CRediT authorship contribution statement

Leonard U. Okonye: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Jianwei Ren:** Writing – review & editing, Resources, Project administration.

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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References

[1] S. Sharifian, N. Asasian-Kolur, Polyethylene terephthalate (PET) waste to carbon materials: theory, methods and applications, J. Anal. Appl. Pyrolysis 163 (2022) 105496, https://doi.org/10.1016/j.jaap.2022.105496.
[2] A. Thakur, P. Devi, Paper-based flexible devices for energy harvesting, conversion and storage applications: a review, Nano Energy 94 (2022) 106927, https://doi.org/10.1016/j.nanoen.2022.106927.
[3] A. Blakers, M. Stocks, B. Lu, C. Cheng, A review of pumped hydro energy storage, Prog Energy 3 (2021) 022003, https://doi.org/10.1088/2516-1083/abeb5b.
[4] S.A. Bhat, V. Kumar, S. Kumar, A.E. Atabani, I. Anjum Badruddin, K.-J. Chae, Supercapacitors production from waste: a new window for sustainable energy and waste management, Fuel 337 (2023) 127125, https://doi.org/10.1016/j.fuel.2022.127125.
[5] A. Dutta, J. Mahanta, T. Banerjee, Supercapacitors in the light of solid waste and energy management: a review, Adv Sustain Syst 4 (2020) 2000182, https://doi.org/10.1002/adsu.202000182.
[6] K. Choudhary, K.S. Sangwan, D. Goyal, Environment and economic impacts assessment of PET waste recycling with conventional and renewable sources of energy, Procedia CIRP 80 (2019) 422–427, https://doi.org/10.1016/j.procir.2019.01.096.
[7] B. Corona, L. Shen, D. Reike, J. Rosales Carreón, E. Worrell, Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics, Resour. Conserv. Recycl. 151 (2019) 104498, https://doi.org/10.1016/j.resconrec.2019.104498.
[8] S. Huang, H. Wang, W. Ahmad, A. Ahmad, N. Ivanovich Vatin, A.M. Mohamed, et al., Plastic waste management strategies and their environmental aspects: a scientometric analysis and comprehensive review, Int. J. Environ. Res. Publ. Health 19 (2022) 4556, https://doi.org/10.3390/ijerph19084556.
[9] K.O. Babaremu, S.A. Okoya, E. Hughes, B. Tijani, D. Teidi, A. Akpan, et al., Sustainable plastic waste management in a circular economy, Heliyon 8 (2022) e09984, https://doi.org/10.1016/j.heliyon.2022.e09984.
[10] L.A. Ángeles-Hurtado, J. Rodríguez-Reséndiz, S. Salazar-Colores, H. Torres-Salinas, P.Y. Sevilla-Camacho, Viable disposal of post-consumer polymers in Mexico: a review, Front. Environ. Sci. 9 (2021), https://doi.org/10.3389/fenvs.2021.749775.
[11] A. Kushwaha, L. Goswami, M. Singhvi, B.S. Kim, Biodegradation of poly(ethylene terephthalate): mechanistic insights, advances, and future innovative strategies, Chem. Eng. J. 457 (2023) 141230, https://doi.org/10.1016/j.cej.2022.141230.

[12] V. Sinha, M.R. Patel, J.V. Patel, Pet waste management by chemical recycling: a review, J. Polym. Environ. 18 (2010) 8–25, https://doi.org/10.1007/s10924-008-0106-7.
[13] F.A. Cruz Sanchez, H. Boudaoud, M. Camargo, J.M. Pearce, Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy, J. Clean. Prod. 264 (2020) 121602, https://doi.org/10.1016/j.jclepro.2020.121602.
[14] D.J. Da Silva, H. Wiebeck, Current options for characterizing, sorting, and recycling polymeric waste, Prog. Rubber Plast. Recycl. Technol. 36 (2020) 284–303, https://doi.org/10.1177/1477760620918603.
[15] E.P. Da Silva, V.H. Fragal, E.H. Fragal, T. Sequinel, L.F. Gorup, R. Silva, et al., Sustainable energy and waste management: how to transform plastic waste into carbon nanostructures for electrochemical supercapacitors, Waste Manag. 171 (2023) 71–85, https://doi.org/10.1016/j.wasman.2023.08.028.
[16] H. Chen, K. Wan, Y. Zhang, Y. Wang, Waste to wealth: chemical recycling and chemical upcycling of waste plastics for a great future, ChemSusChem 14 (2021) 4123–4136, https://doi.org/10.1002/cssc.202100652.
[17] R.C. Thompson, C.J. Moore, F.S. vom Saal, S.H. Swan, Plastics, the environment and human health: current consensus and future trends, Philos. Trans. R. Soc. Lond. B Biol. Sci. 364 (2009) 2153–2166, https://doi.org/10.1098/rstb.2009.0053.
[18] E.M. Bennett, P. Alexandridis, Informing the public and educating students on plastic recycling, Recycling 6 (2021) 69, https://doi.org/10.3390/recycling6040069.
[19] P. Sarda, J.C. Hanan, J.G. Lawrence, M. Allahkarami, Sustainability performance of polyethylene terephthalate, clarifying challenges and opportunities, J. Polym. Sci. 60 (2022) 7–31, https://doi.org/10.1002/pol.20210495.
[20] A. Ncube, S. Mtetwa, M. Bukhari, G. Fiorentino, R. Passaro, Circular economy and green chemistry: the need for radical innovative approaches in the design for new products, Energies 16 (2023) 1752, https://doi.org/10.3390/en16041752.
[21] R.L. Smith, S. Takkellapati, R.C. Riegerix, Recycling of plastics in the United States: plastic material flows and polyethylene terephthalate (PET) recycling processes, ACS Sustain. Chem. Eng. 10 (2022) 2084–2096, https://doi.org/10.1021/acssuschemeng.1c06845.
[22] B.G. Mwanza, C. Mbohwa, Drivers to sustainable plastic solid waste recycling: a review, Procedia Manuf. 8 (2017) 649–656, https://doi.org/10.1016/j.promfg.2017.02.083.
[23] I. Vollmer, M.J.F. Jenks, M.C.P. Roelands, R.J. White, T. van Harmelen, P. de Wild, et al., Beyond mechanical recycling: giving new life to plastic waste, Angew. Chem. Int. Ed. 59 (2020) 15402–15423, https://doi.org/10.1002/anie.201915651.
[24] M. Khoonkari, A.H. Haghighi, Y. Sefidbakht, K. Shekoohi, A. Ghaderian, Chemical recycling of PET wastes with different catalysts, Int J Polym Sci 2015 (2015) 1–11, https://doi.org/10.1155/2015/124524.
[25] A. Rahimi, J.M. García, Chemical recycling of waste plastics for new materials production, Nat. Rev. Chem 1 (2017) 1–11, https://doi.org/10.1038/s41570-017-0046.
[26] Z.O.G. Schyns, M.P. Shaver, Mechanical recycling of packaging plastics: a review, Macromol. Rapid Commun. 42 (2021) 2000415, https://doi.org/10.1002/marc.202000415.
[27] L. Trossaert, M. De Vel, L. Cardon, M. Edeleva, Lifting the sustainability of modified pet-based multilayer packaging material with enhanced mechanical recycling potential and processing, Polymers 14 (2022) 196, https://doi.org/10.3390/polym14010196.
[28] M. Frounchi, Studies on degradation of PET in mechanical recycling, Macromol. Symp. 144 (1999) 465–469, https://doi.org/10.1002/masy.19991440142.
[29] AM de Castro, A. Carniel, A novel process for poly(ethylene terephthalate) depolymerization via enzyme-catalyzed glycolysis, Biochem. Eng. J. 124 (2017) 64–68, https://doi.org/10.1016/j.bej.2017.04.011.
[30] E. Naderi Kalali, S. Lotfian, M. Entezar Shabestari, S. Khayatzadeh, C. Zhao, H. Yazdani Nezhad, A critical review of the current progress of plastic waste recycling technology in structural materials, Curr. Opin. Green Sustainable Chem. 40 (2023) 100763, https://doi.org/10.1016/j.cogsc.2023.100763.
[31] A. Bashirgonbadi, I. Saputra Lase, L. Delva, K.M. Van Geem, S. De Meester, K. Ragaert, Quality evaluation and economic assessment of an improved mechanical recycling process for post-consumer flexible plastics, Waste Manag. 153 (2022) 41–51, https://doi.org/10.1016/j.wasman.2022.08.018.
[32] E. Mendiburu-Valor, G. Mondragon, N. González, G. Kortaberria, L. Martin, A. Eceiza, et al., Valorization of urban and marine PET waste by optimized chemical recycling, Resour. Conserv. Recycl. 184 (2022) 106413, https://doi.org/10.1016/j.resconrec.2022.106413.
[33] E.I.M. Bardoquillo, J.M.B. Firman, D.B. Montecastro, A.M. Basilio, Chemical recycling of waste polyethylene terephthalate (PET) bottles via recovery and polymerization of terephthalic acid (TPA) and ethylene glycol (EG), Mater. Today Proc. (2023), https://doi.org/10.1016/j.matpr.2023.04.160. S2214785323020564.
[34] A. Sheel, D. Pant, Chemical depolymerization of PET bottles via glycolysis, Recycl. Polyethyl. Terephthalate Bottles (2019) 61–84, https://doi.org/10.1016/B978-0-12-811361-5.00004-3. Elsevier.
[35] Y. Hu, Y. Wang, X. Zhang, J. Qian, X. Xing, X. Wang, Synthesis of poly(ethylene terephthalate) based on glycolysis of waste PET fiber, J. Macromol. Sci. Part A 57 (2020) 430–438, https://doi.org/10.1080/10601325.2019.1709498.
[36] H. Abedsoltan, A focused review on recycling and hydrolysis techniques of polyethylene terephthalate, Polym. Eng. Sci. 63 (2023) 2651–2674, https://doi.org/10.1002/pen.26406.
[37] E. Mendiburu-Valor, G. Mondragon, N. González, G. Kortaberria, A. Eceiza, C. Peña-Rodriguez, Improving the efficiency for the production of bis-(2-hydroxyethyl) terephtalate (BHET) from the glycolysis reaction of poly(ethylene terephtalate) (PET) in a pressure reactor, Polymers 13 (2021) 1461, https://doi.org/10.3390/polym13091461.
[38] M. Han, Depolymerization of PET bottle via methanolysis and hydrolysis, Recycl. Polyethyl. Terephthalate Bottles (2019) 85–108, https://doi.org/10.1016/B978-0-12-811361-5.00005-5. Elsevier.
[39] Z. Jiang, D. Yan, J. Xin, F. Li, M. Guo, Q. Zhou, et al., Poly(ionic liquid)s as efficient and recyclable catalysts for methanolysis of PET, Polym. Degrad. Stabil. 199 (2022) 109905, https://doi.org/10.1016/j.polymdegradstab.2022.109905.
[40] T. Thiounn, R.C. Smith, Advances and approaches for chemical recycling of plastic waste, J. Polym. Sci. 58 (2020) 1347–1364, https://doi.org/10.1002/pol.20190261.
[41] B. Zhu, D. Wang, N. Wei, Enzyme discovery and engineering for sustainable plastic recycling, Trends Biotechnol. 40 (2022) 22–37, https://doi.org/10.1016/j.tibtech.2021.02.008.
[42] M.J. Kang, H.J. Yu, J. Jegal, H.S. Kim, H.G. Cha, Depolymerization of PET into terephthalic acid in neutral media catalyzed by the ZSM-5 acidic catalyst, Chem. Eng. J. 398 (2020) 125655, https://doi.org/10.1016/j.cej.2020.125655.
[43] E. Selvam, Y. Luo, M. Ierapetritou, R.F. Lobo, D.G. Vlachos, Microwave-assisted depolymerization of PET over heterogeneous catalysts, Catal. Today 418 (2023) 114124, https://doi.org/10.1016/j.cattod.2023.114124.
[44] R. Brackmann, C. de Oliveira Veloso, A.M. de Castro, M.A.P. Langone, Enzymatic post-consumer poly(ethylene terephthalate) (PET) depolymerization using commercial enzymes, 3 Biotech 13 (2023) 135, https://doi.org/10.1007/s13205-023-03555-6.
[45] A. Carniel, V.D.A. Waldow, A.M.D. Castro, A comprehensive and critical review on key elements to implement enzymatic PET depolymerization for recycling purposes, Biotechnol. Adv. 52 (2021) 107811, https://doi.org/10.1016/j.biotechadv.2021.107811.
[46] M.M. Harussani, S.M. Sapuan, U. Rashid, A. Khalina, R.A. Ilyas, Pyrolysis of polypropylene plastic waste into carbonaceous char: priority of plastic waste management amidst COVID-19 pandemic, Sci. Total Environ. 803 (2022) 149911, https://doi.org/10.1016/j.scitotenv.2021.149911.
[47] Y. Liu, W. Fu, T. Liu, Y. Zhang, B. Li, Microwave pyrolysis of polyethylene terephthalate (PET) plastic bottle sheets for energy recovery, J. Anal. Appl. Pyrolysis 161 (2022) 105414, https://doi.org/10.1016/j.jaap.2021.105414.
[48] D.V. Suriapparao, R. Tejasvi, A review on role of process parameters on pyrolysis of biomass and plastics: present scope and future opportunities in conventional and microwave-assisted pyrolysis technologies, Process Saf. Environ. Protect. 162 (2022) 435–462, https://doi.org/10.1016/j.psep.2022.04.024.
[49] F. Kawai, Y. Furushima, N. Mochizuki, N. Muraki, M. Yamashita, A. Iida, et al., Efficient depolymerization of polyethylene terephthalate (PET) and polyethylene furanoate by engineered PET hydrolase Cut190, Amb. Express 12 (2022) 134, https://doi.org/10.1186/s13568-022-01474-y.
[50] G. Grause, A. Buekens, Y. Sakata, A. Okuwaki, T. Yoshioka, Feedstock recycling of waste polymeric material, J. Mater. Cycles Waste Manag. 13 (2011) 265–282, https://doi.org/10.1007/s10163-011-0031-z.

[51] K. Babaremu, A. Adediji, N. Olumba, S. Okoya, E. Akinlabi, M. Oyinlola, Technological advances in mechanical recycling innovations and corresponding impacts on the circular economy of plastics, Environments 11 (2024) 38, https://doi.org/10.3390/environments11030038.
[52] M.C. Mulakkal, A. Castillo Castillo, A.C. Taylor, B.R.K. Blackman, D.S. Balint, S. Pimenta, et al., Advancing mechanical recycling of multilayer plastics through finite element modelling and environmental policy, Resour. Conserv. Recycl. 166 (2021) 105371, https://doi.org/10.1016/j.resconrec.2020.105371.
[53] I.S. Lase, A. Bashirgonbadi, F. Van Rhijn, J. Dewulf, K. Ragaert, L. Delva, et al., Material flow analysis and recycling performance of an improved mechanical recycling process for post-consumer flexible plastics, Waste Manag. 153 (2022) 249–263, https://doi.org/10.1016/j.wasman.2022.09.002.
[54] M. Crippa, B. Morico, PET depolymerization: a novel process for plastic waste chemical recycling, Stud. Surf. Sci. Catal. 179 (2020) 215–229, https://doi.org/10.1016/B978-0-444-64337-7.00012-4. Elsevier.
[55] A. Bohre, P.R. Jadhao, K. Tripathi, K.K. Pant, B. Likozar, B. Saha, Chemical recycling processes of waste polyethylene terephthalate using solid catalysts, ChemSusChem 16 (2023) e202300142, https://doi.org/10.1002/cssc.202300142.
[56] A. Singh, P.P. Kundu, K. Kumari, S.L. Banerjee, Recent innovations in chemical recycling of polyethylene terephthalate waste: a circular economy approach toward sustainability, in: C. Baskar, S. Ramakrishna, S. Baskar, R. Sharma, A. Chinnappan, R. Sehrawat (Eds.), Handb. Solid Waste Manag. Sustain. Circ. Econ., Springer Nature Singapore, Singapore, 2022, https://doi.org/10.1007/978-981-16-4230-2.
[57] Q. Duan, J. Li, Classification of Common household plastic wastes combining multiple methods based on near-infrared spectroscopy, ACS EST Eng 1 (2021) 1065–1073, https://doi.org/10.1021/acsestengg.0c00183.
[58] T. Zhang, X. Li, J. Wang, Y. Miao, T. Wang, X. Qian, et al., Photovoltaic-driven electrocatalytic upcycling poly(ethylene terephthalate) plastic waste coupled with hydrogen generation, J. Hazard Mater. 450 (2023) 131054, https://doi.org/10.1016/j.jhazmat.2023.131054.
[59] Y. Luo, E. Selvam, D.G. Vlachos, M. Ierapetritou, Economic and environmental benefits of modular microwave-assisted polyethylene terephthalate depolymerization, ACS Sustain. Chem. Eng. 11 (2023) 4209–4218, https://doi.org/10.1021/acssuschemeng.2c07203.
[60] R. Wei, G. von Haugwitz, L. Pfaff, J. Mican, C.P.S. Badenhorst, W. Liu, et al., Mechanism-based design of efficient PET hydrolases, ACS Catal. 12 (2022) 3382–3396, https://doi.org/10.1021/acscatal.1c05856.
[61] A. Preetam, P.R. Jadhao, S.N. Naik, K.K. Pant, V. Kumar, Supercritical fluid technology - an eco-friendly approach for resource recovery from e-waste and plastic waste: a review, Sep. Purif. Technol. 304 (2023) 122314, https://doi.org/10.1016/j.seppur.2022.122314.
[62] I.V. Elmanovich, V.E. Sizov, V.V. Zefirov, A.A. Kalinina, M.O. Gallyamov, V.S. Papkov, et al., Chemical recycling of high-molecular-weight organosilicon compounds in supercritical fluids, Polymers 14 (2022) 5170, https://doi.org/10.3390/polym14235170.
[63] J. Zhao, A.F. Burke, Review on supercapacitors: technologies and performance evaluation, J. Energy Chem. 59 (2021) 276–291, https://doi.org/10.1016/j.jechem.2020.11.013.
[64] Y. Wang, X. Wu, Y. Han, T. Li, Flexible supercapacitor: overview and outlooks, J. Energy Storage 42 (2021) 103053, https://doi.org/10.1016/j.est.2021.103053.
[65] L. Yaqoob, T. Noor, N. Iqbal, Conversion of plastic waste to carbon-based compounds and application in energy storage devices, ACS Omega 7 (2022) 13403–13435, https://doi.org/10.1021/acsomega.1c07291.
[66] A. Berrueta, A. Ursua, I.S. Martin, A. Eftekhari, P. Sanchis, Supercapacitors: electrical characteristics, modeling, applications, and future trends, IEEE Access 7 (2019) 50869–50896, https://doi.org/10.1109/ACCESS.2019.2908558.
[67] S.A. Bhat, V. Kumar, S. Kumar, A.E. Atabani, I. Anjum Badruddin, K.-J. Chae, Supercapacitors production from waste: a new window for sustainable energy and waste management, Fuel 337 (2023) 127125, https://doi.org/10.1016/j.fuel.2022.127125.
[68] S. Kumar, G. Saeed, L. Zhu, K.N. Hui, N.H. Kim, J.H. Lee, 0D to 3D carbon-based networks combined with pseudocapacitive electrode material for high energy density supercapacitor: a review, Chem. Eng. J. 403 (2021) 126352, https://doi.org/10.1016/j.cej.2020.126352.
[69] M.S. Asl, R. Hadi, L. Salehghadimi, A.G. Tabrizi, S. Farhoudian, A. Babapoor, et al., Flexible all-solid-state supercapacitors with high capacitance, long cycle life, and wide operational potential window: recent progress and future perspectives, J. Energy Storage 50 (2022) 104223, https://doi.org/10.1016/j.est.2022.104223.
[70] A. Afif, S.M. Rahman, A. Tasfiah Azad, J. Zaini, M.A. Islan, A.K. Azad, Advanced materials and technologies for hybrid supercapacitors for energy storage – a review, J. Energy Storage 25 (2019) 100852, https://doi.org/10.1016/j.est.2019.100852.
[71] Sharma K. Poonam, A. Arora, S.K. Tripathi, Review of supercapacitors: materials and devices, J. Energy Storage 21 (2019) 801–825, https://doi.org/10.1016/j.est.2019.01.010.
[72] A. Muzaffar, M.B. Ahamed, K. Deshmukh, J. Thirumalai, A review on recent advances in hybrid supercapacitors: design, fabrication and applications, Renew. Sustain. Energy Rev. 101 (2019) 123–145, https://doi.org/10.1016/j.rser.2018.10.026.
[73] M.E. Şahin, F. Blaabjerg, A. Sangwongwanich, A comprehensive review on supercapacitor applications and developments, Energies 15 (2022) 674, https://doi.org/10.3390/en15030674.
[74] R. Muniraj, N. Karuppiah, P.V. Nisha, M.B. Chandran, T. Jarin, S. Akkara, A comparative analysis on supercapacitor based HEV, AIP Conf. Proc. 2690 (2023) 020064, https://doi.org/10.1063/5.0120011.
[75] J. Chen, P.S. Lee, Electrochemical supercapacitors: from mechanism understanding to multifunctional applications, Adv. Energy Mater. 11 (2021) 2003311, https://doi.org/10.1002/aenm.202003311.
[76] M. Karakoti, S. Pandey, G. Tatrari, S.C. Sati, N.G. Sahoo, Recycling of plastics into advance carbon nanomaterials and their application in energy storage system, in: J. Parameswaranpillai, S. Mavinkere Rangappa, A. Gulihonnehalli Rajkumar, S. Siengchin (Eds.), Recent Dev. Plast. Recycl., Springer, Singapore, 2021, pp. 259–281, https://doi.org/10.1007/978-981-16-3627-1_12.
[77] Nayak S. Kumar, S.M. Saurabh, A. Kar, B. Bhusan Sahoo, N. Kumar Sahoo, P. Kumar Sahoo, Advances in plastic waste-derived carbon nanomaterial for supercapacitor applications: trends, challenges and prospective, Mater. Today Proc. 67 (2022) 1024–1032, https://doi.org/10.1016/j.matpr.2022.05.519.
[78] A. Allagui, A.S. Elwakil, M.E. Fouda, A.G. Radwan, Capacitive behavior and stored energy in supercapacitors at power line frequencies, J. Power Sources 390 (2018) 142–147, https://doi.org/10.1016/j.jpowsour.2018.04.035.
[79] D.P. Chatterjee, A.K. Nandi, A review on the recent advances in hybrid supercapacitors, J. Mater. Chem. A 9 (2021) 15880–15918, https://doi.org/10.1039/D1TA02505H.
[80] S. Huang, X. Zhu, S. Sarkar, Y. Zhao, Challenges and opportunities for supercapacitors, Apl. Mater. 7 (2019) 100901, https://doi.org/10.1063/1.5116146.
[81] A. Daraghmeh, S. Hussain, A.U. Haq, I. Saadeddin, L. Servera, J. Ruiz, Carbon nanocomposite electrodes for electrical double layer capacitor, J. Energy Storage 32 (2020) 101798, https://doi.org/10.1016/j.est.2020.101798.
[82] R. Kunwar, B. Pal, I. Izwan Misnon, H. Daniyal, F. Zabihi, S. Yang, et al., Characterization of electrochemical double layer capacitor electrode using self-discharge measurements and modeling, Appl. Energy 334 (2023) 120658, https://doi.org/10.1016/j.apenergy.2023.120658.
[83] W. Gu, M. Sevilla, A. Magasinski, A.B. Fuertes, G. Yushin, Sulfur-containing activated carbons with greatly reduced content of bottle neck pores for double-layer capacitors: a case study for pseudocapacitance detection, Energy Environ. Sci. 6 (2013) 2465–2476, https://doi.org/10.1039/C3EE41182F.
[84] X. Chen, R. Paul, L. Dai, Carbon-based supercapacitors for efficient energy storage, Natl. Sci. Rev. 4 (2017) 453–489, https://doi.org/10.1093/nsr/nwx009.
[85] W. Jiang, D. Yu, Q. Zhang, K. Goh, L. Wei, Y. Yong, et al., Ternary hybrids of amorphous nickel hydroxide–carbon nanotube-conducting polymer for supercapacitors with high energy density, excellent rate capability, and long cycle life, Adv. Funct. Mater. 25 (2015) 1063–1073, https://doi.org/10.1002/adfm.201403354.
[86] I. Mukkatt, A.P. Mohanachandran, A. Nirmala, D. Patra, P.A. Sukumaran, R.S. Pillai, et al., Tunable capacitive behavior in metallopolymer-based electrochromic thin film supercapacitors, ACS Appl. Mater. Interfaces 14 (2022) 31900–31910, https://doi.org/10.1021/acsami.2c05744.
[87] K.S. Lee, Y.J. Seo, H.T. Jeong, Capacitive behavior of functionalized activated carbon-based all-solid-state supercapacitor, Carbon Lett 31 (2021) 1041–1049, https://doi.org/10.1007/s42823-020-00219-w.
[88] J. Lang, X. Zhang, L. Liu, B. Yang, J. Yang, X. Yan, Highly enhanced energy density of supercapacitors at extremely low temperatures, J. Power Sources 423 (2019) 271–279, https://doi.org/10.1016/j.jpowsour.2019.03.096.

[89] A. Slonopas, H. Ryan, P. Norris, Ultrahigh energy density CH3NH3PbI3 perovskite based supercapacitor with fast discharge, Electrochim. Acta 307 (2019) 334–340, https://doi.org/10.1016/j.electacta.2019.03.221.

[90] Q. Wu, T. He, Y. Zhang, J. Zhang, Z. Wang, Y. Liu, et al., Cyclic stability of supercapacitors: materials, energy storage mechanism, test methods, and device, J. Mater. Chem. A 9 (2021) 24094–24147, https://doi.org/10.1039/D1TA06815F.

[91] M. Jung, I. Yang, D. Choi, J. Lee, J.C. Jung, Activated carbons derived from polyethylene terephthalate for coin-cell supercapacitor electrodes, Kor. J. Chem. Eng. (2023), https://doi.org/10.1007/s11814-023-1466-3.

[92] Y. Wang, L. Zhang, H. Hou, W. Xu, G. Duan, S. He, et al., Recent progress in carbon-based materials for supercapacitor electrodes: a review, J. Mater. Sci. 56 (2021) 173–200, https://doi.org/10.1007/s10853-020-05157-6.

[93] M. Jiang, X. Wang, W. Xi, H. Zhou, P. Yang, J. Yao, et al., Upcycling plastic waste to carbon materials for electrochemical energy storage and conversion, Chem. Eng. J. 461 (2023) 141962, https://doi.org/10.1016/j.cej.2023.141962.

[94] R. Banavath, S.S. Nemala, S.-H. Kim, S. Bohm, M.Z. Ansari, D. Mohapatra, et al., Industrially scalable exfoliated graphene nanoplatelets by high-pressure airless spray technique for high-performance supercapacitors, FlatChem 33 (2022) 100373, https://doi.org/10.1016/j.flatc.2022.100373.

[95] M. Dai, D. Zhao, X. Wu, Research progress on transition metal oxide based electrode materials for asymmetric hybrid capacitors, Chin. Chem. Lett. 31 (2020) 2177–2188, https://doi.org/10.1016/j.cclet.2020.02.017.

[96] B. De, S. Banerjee, K.D. Verma, T. Pal, P.K. Manna, K.K. Kar, Transition metal oxides as electrode materials for supercapacitors, in: K.K. Kar (Ed.), Handb. Nanocomposite Supercapacitor Mater. II Perform., Springer International Publishing, Cham, 2020, pp. 89–111, https://doi.org/10.1007/978-3-030-52359-6_4.

[97] M. Deyab N, M. Taha M, K. Allam N, A mesoporous ternary transition metal oxide nanoparticle composite for high-performance asymmetric supercapacitor devices with high specific energy, Nanoscale Adv. 4 (2022) 1387–1393, https://doi.org/10.1039/D1NA00694K.

[98] A. Pramitha, S.S. Hegde, B.R. Bhat, S.D. George, Y.N. Sudhakar, Y. Raviprakash, Properties of Mn3O4 thin film electrodes prepared using spray pyrolysis for supercapacitor application, Mater. Chem. Phys. 307 (2023) 128213, https://doi.org/10.1016/j.matchemphys.2023.128213.

[99] P. Adoor, S.S. Hegde, B.R. Bhat, S.N. Yethadka, R. Yeenduguli, Elucidating the role of copper-induced mixed phases on the electrochemical performance of Mn-based thin-film electrodes, ACS Omega 8 (2023) 46640–46652, https://doi.org/10.1021/acsomega.3c05614.

[100] Bhaskaran Shobha, S.K. Gupta, High super capacitive performance of mixed transition and inner transition metal oxide-based hybrid nanostructures, Mater. Today Proc. 43 (2021) 3221–3224, https://doi.org/10.1016/j.matpr.2021.01.887.

[101] S. Dutta, S. Pal, S. De, Mixed solvent exfoliated transition metal oxides nanosheets based flexible solid state supercapacitor devices endowed with high energy density, New J. Chem. 43 (2019) 12385–12395, https://doi.org/10.1039/C9NJ03233A.

[102] J. Fu, X. Jiang, W. Han, Z. Cao, Enhancing the cycling stability of transition-metal-oxide-based electrochemical electrode via pourbaix diagram engineering, Energy Storage Mater. 42 (2021) 252–258, https://doi.org/10.1016/j.ensm.2021.07.037.

[103] M. Guan, Q. Wang, X. Zhang, J. Bao, X. Gong, Y. Liu, Two-dimensional transition metal oxide and hydroxide-based hierarchical architectures for advanced supercapacitor materials, Front. Chem. 8 (2020).

[104] R.S. Santos, Babu R. Suresh, M. Devendiran, D.B. Haddad, ALF de Barros, Facile synthesis of transition metal (M = Cu, Co) oxide grafted graphitic carbon nitride nanosheets for high performance asymmetric supercapacitors, Mater. Lett. 308 (2022) 131156, https://doi.org/10.1016/j.matlet.2021.131156.

[105] P. Sivakumar, M.G. Jung, C.J. Raj, J. Park, H.S. Park, H. Jung, Nanowire architectured porous bimetallic transition metal oxides for high performance hybrid supercapacitor applications, Int. J. Energy Res. 45 (2021) 18091–18102, https://doi.org/10.1002/er.6954.

[106] S.N.A. Baharin, R. Rusmin, K.P. Sambasevam, Basic concept and application of conducting polymers for environmental protection, Chem Teach Int 4 (2022) 173–183, https://doi.org/10.1515/cti-2021-0041.

[107] W. Chen, C. Xia, R.B. Rakhi, H.N. Alshareef, A general approach toward enhancement of pseudocapacitive performance of conducting polymers by redox-active electrolytes, J. Power Sources 267 (2014) 521–526, https://doi.org/10.1016/j.jpowsour.2014.05.131.

[108] N.N. Loganathan, V. Perumal, B.R. Pandian, R. Atchudan, T.N.J.I. Edison, M. Ovinis, Recent studies on polymeric materials for supercapacitor development, J. Energy Storage 49 (2022) 104149, https://doi.org/10.1016/j.est.2022.104149.

[109] K. Namsheer, C.S. Rout, Conducting polymers: a comprehensive review on recent advances in synthesis, properties and applications, RSC Adv. 11 (2021) 5659–5697, https://doi.org/10.1039/D0RA07800J.

[110] T. Nezakati, A. Seifalian, A. Tan, A.M. Seifalian, Conductive polymers: opportunities and challenges in biomedical applications, Chem. Rev. 118 (2018) 6766–6843, https://doi.org/10.1021/acs.chemrev.6b00275.

[111] S. Sharma, P. Sudhakara, A.A.B. Omran, J. Singh, R.A. Ilyas, Recent trends and developments in conducting polymer nanocomposites for multifunctional applications, Polymers 13 (2021) 2898, https://doi.org/10.3390/polym13172898.

[112] S. Suriyakumar, P. Bhardwaj, A.N. Grace, A.M. Stephan, Role of polymers in enhancing the performance of electrochemical supercapacitors: a review, Batter Supercaps 4 (2021) 571–584, https://doi.org/10.1002/batt.202000272.

[113] D.B. Bailmare, S.J. Dhoble, A.D. Deshmukh, Metal organic frameworks and their derived materials for capacity enhancement of supercapacitors: progress and perspective, Synth. Met. 282 (2021) 116945, https://doi.org/10.1016/j.synthmet.2021.116945.

[114] E. Doustkhah, R. Hassandoost, A. Khataee, R. Luque, M.H.N. Assadi, Hard-templated metal–organic frameworks for advanced applications, Chem. Soc. Rev. 50 (2021) 2927–2953, https://doi.org/10.1039/C9CS00813F.

[115] P. Dubey, V. Shrivastav, P.H. Maheshwari, M. Hołdyński, A. Krawczyńska, S. Sundriyal, Comparative study of different metal-organic framework electrodes synthesized using waste PET bottles for supercapacitor applications, J. Energy Storage 68 (2023) 107828, https://doi.org/10.1016/j.est.2023.107828.

[116] A. Mohanty, D. Jaihindh, Y.-P. Fu, S.P. Senanayak, L.S. Mende, A. Ramadoss, An extensive review on three dimension architectural Metal-Organic Frameworks towards supercapacitor application, J. Power Sources 488 (2021) 229444, https://doi.org/10.1016/j.jpowsour.2020.229444.

[117] X. Zhao, L. Gong, C. Wang, C. Wang, K. Yu, B. Zhou, A facile grinding method for the synthesis of 3D Ag metal–organic frameworks (MOFs) containing Ag6Mo7O24 for high-performance supercapacitors, Chem. Eur J. 26 (2020) 4613–4619, https://doi.org/10.1002/chem.201905689.

[118] T. Wu, Z. Ma, Y. He, X. Wu, B. Tang, Z. Yu, et al., A covalent black phosphorus/metal–organic framework hetero-nanostructure for high-performance flexible supercapacitors, Angew. Chem. Int. Ed. 60 (2021) 10366–10374, https://doi.org/10.1002/anie.202101648.

[119] B. Padha, S. Verma, S. Arya, Fabric-based wearable self-powered asymmetric supercapacitor comprising lead-free perovskite piezoelectrodes, Adv Mater Technol 7 (2022) 2200079, https://doi.org/10.1002/admt.202200079.

[120] R. Kumar, M. Bag, Hybrid halide perovskite-based electrochemical supercapacitors: recent progress and perspective, Energy Technol. 10 (2022) 2100889, https://doi.org/10.1002/ente.202100889.

[121] S.S. Hegde, B.R. Bhat, Biomass waste-derived porous graphitic carbon for high-performance supercapacitors, J. Energy Storage 76 (2024) 109818, https://doi.org/10.1016/j.est.2023.109818.

[122] S.S. Hegde, B.R. Bhat, Sustainable energy storage: mangifera indica leaf waste-derived activated carbon for long-life, high-performance supercapacitors, RSC Adv. 14 (2024) 8028–8038, https://doi.org/10.1039/D3RA08910J.

[123] S. Subraya Hegde, B. Ramachandra Bhat, Impact of electrolyte concentration on electrochemical performance of Cocos nucifera Waste-Derived High-Surface carbon for green energy storage, Fuel 371 (2024) 131999, https://doi.org/10.1016/j.fuel.2024.131999.

[124] D. Zhang, Z. Ma, Y. Zhang, Y. Xu, H. Liu, J. Wu, et al., Activated carbon tailored by potassium hydroxide from waste tires as a supercapacitor electrode, ECS J Solid State Sci Technol 11 (2022) 061004, https://doi.org/10.1149/2162-8777/ac7611.

[125] C.-C. Chen, Y.-H. Huang, H.-J. Chien, Waste tire-derived porous nitrogen-doped carbon black as an electrode material for supercapacitors, Sustain Chem Pharm 24 (2021) 100535, https://doi.org/10.1016/j.scp.2021.100535.

[126] N.R. Chodankar, S.J. Patil, S.-K. Hwang, P.A. Shinde, S.V. Karekar, G.S.R. Raju, et al., Refurbished carbon materials from waste supercapacitors as industrial-grade electrodes: empowering electronic waste, Energy Storage Mater. 49 (2022) 564–574, https://doi.org/10.1016/j.ensm.2022.04.039.

[127] W. Fan, Q. Wang, K. Rong, Y. Shi, W. Peng, H. Li, et al., MXene enhanced 3D needled waste denim felt for high-performance flexible supercapacitors, Nano-Micro Lett. 16 (2023) 36, https://doi.org/10.1007/s40820-023-01226-y.

[128] A.M. Al-Enizi, M. Ubaidullah, J. Ahmed, T. Ahamad, T. Ahmad, S.F. Shaikh, et al., Synthesis of NiOx@NPC composite for high-performance supercapacitor via waste PET plastic-derived Ni-MOF, Composites, Part B 183 (2020) 107655, https://doi.org/10.1016/j.compositesb.2019.107655.
[129] M. Kigozi, G.N. Kasozi, S. Balaso Mohite, S. Zamisa, R. Karpoormath, J.B. Kirabira, et al., Non-emission hydrothermal low-temperature synthesis of carbon nanomaterials from poly (ethylene terephthalate) plastic waste for excellent supercapacitor applications, Green Chem. Lett. Rev. 16 (2023) 2173025, https://doi.org/10.1080/17518253.2023.2173025.
[130] A. Mirjalili, B. Dong, P. Pena, C.S. Ozkan, M. Ozkan, Upcycling of polyethylene terephthalate plastic waste to microporous carbon structure for energy storage, Energy Storage 2 (2020) e201, https://doi.org/10.1002/est2.201.
[131] H. Zhang, X.-L. Zhou, L.-M. Shao, F. Lü, P.-J. He, Upcycling of PET waste into methane-rich gas and hierarchical porous carbon for high-performance supercapacitor by autogenic pressure pyrolysis and activation, Sci. Total Environ. 772 (2021) 145309, https://doi.org/10.1016/j.scitotenv.2021.145309.
[132] J. Gong, X. Chen, T. Tang, Recent progress in controlled carbonization of (waste) polymers, Prog. Polym. Sci. 94 (2019) 1–32, https://doi.org/10.1016/j.progpolymsci.2019.04.001.
[133] X. Mu, Y. Li, X. Liu, C. Ma, H. Jiang, J. Zhu, et al., Controllable carbonization of plastic waste into three-dimensional porous carbon nanosheets by combined catalyst for high performance capacitor, Nanomaterials 10 (2020) 1097, https://doi.org/10.3390/nano10061097.
[134] N.A. Salleh, S. Kheawhom, A. Ashrina, N. Hamid, W. Rahiman, A.A. Mohamad, Electrode polymer binders for supercapacitor applications: a review, J. Mater. Res. Technol. 23 (2023) 3470–3491, https://doi.org/10.1016/j.jmrt.2023.02.013.
[135] R. Na, N. Lu, L. Li, Y. Liu, J. Luan, G. Wang, A robust conductive polymer network as a multi-functional binder and conductive additive for supercapacitors, Chemelectrochem 7 (2020) 3056–3064, https://doi.org/10.1002/celc.202000726.
[136] M. Ubaidullah, A.M. Al-Enizi, T. Ahamad, S.F. Shaikh, M.A. Al-Abdrabalnabi, M.S. Samdani, et al., Fabrication of highly porous N-doped mesoporous carbon using waste polyethylene terephthalate bottle-based MOF-5 for high performance supercapacitor, J. Energy Storage 33 (2021) 102125, https://doi.org/10.1016/j.est.2020.102125.
[137] M. Karakoti, S. Pandey, R. Jangra, P.S. Dhapola, P.K. Singh, S. Mahendia, et al., Waste plastics derived graphene nanosheets for supercapacitor application, Mater. Manuf. Process. 36 (2021) 171–177, https://doi.org/10.1080/10426914.2020.1832680.
[138] Y. Wen, K. Kierzek, J. Min, X. Chen, J. Gong, R. Niu, et al., Porous carbon nanosheet with high surface area derived from waste poly(ethylene terephthalate) for supercapacitor applications, J. Appl. Polym. Sci. 137 (2020) 48338, https://doi.org/10.1002/app.48338.
[139] Y. Wen, K. Kierzek, X. Chen, J. Gong, J. Liu, R. Niu, et al., Mass production of hierarchically porous carbon nanosheets by carbonizing “real-world” mixed waste plastics toward excellent-performance supercapacitors, Waste Manag. 87 (2019) 691–700, https://doi.org/10.1016/j.wasman.2019.03.006.
[140] X. Liu, Y. Wen, X. Chen, T. Tang, E. Mijowska, Co-etching effect to convert waste polyethylene terephthalate into hierarchical porous carbon toward excellent capacitive energy storage, Sci. Total Environ. 723 (2020) 138055, https://doi.org/10.1016/j.scitotenv.2020.138055.
[141] W. Utetiwabo, L. Yang, M.K. Tufail, L. Zhou, R. Chen, Y. Lian, et al., Electrode materials derived from plastic wastes and other industrial wastes for supercapacitors, Chin. Chem. Lett. 31 (2020) 1474–1489, https://doi.org/10.1016/j.cclet.2020.01.003.
[142] C. Ma, X. Liu, J. Min, J. Li, J. Gong, X. Wen, et al., Sustainable recycling of waste polystyrene into hierarchical porous carbon nanosheets with potential applications in supercapacitors, Nanotechnology 31 (2020) 035402, https://doi.org/10.1088/1361-6528/ab475f.
[143] J. Min, S. Zhang, J. Li, R. Klingeler, X. Wen, X. Chen, et al., From polystyrene waste to porous carbon flake and potential application in supercapacitor, Waste Manag. 85 (2019) 333–340, https://doi.org/10.1016/j.wasman.2019.01.002.
[144] D.W. Lee, J.W. Seo, sp2/sp3 carbon ratio in graphite oxide with different preparation times, J. Phys. Chem. C 115 (2011) 2705–2708, https://doi.org/10.1021/jp107906u.
[145] O.I. Nkwachukwu, C.H. Chima, A.O. Ikenna, L. Albert, Focus on potential environmental issues on plastic world towards a sustainable plastic recycling in developing countries, Int J Ind Chem 4 (2013) 34, https://doi.org/10.1186/2228-5547-4-34.
[146] J. Zhang, M. Gu, X. Chen, Supercapacitors for renewable energy applications: a review, Micro Nano Eng 21 (2023) 100229, https://doi.org/10.1016/j.mne.2023.100229.
[147] M. Cossutta, V. Vretenar, T.A. Centeno, P. Kotrusz, J. McKechnie, S.J. Pickering, A comparative life cycle assessment of graphene and activated carbon in a supercapacitor application, J. Clean. Prod. 242 (2020) 118468, https://doi.org/10.1016/j.jclepro.2019.118468.
[148] R. Vellacheri, A. Al-Haddad, H. Zhao, W. Wang, C. Wang, Y. Lei, High performance supercapacitor for efficient energy storage under extreme environmental temperatures, Nano Energy 8 (2014) 231–237, https://doi.org/10.1016/j.nanoen.2014.06.015.
[149] M.F. Elmorshedy, M.R. Elkadeem, K.M. Kotb, I.B.M. Taha, D. Mazzeo, Optimal design and energy management of an isolated fully renewable energy system integrating batteries and supercapacitors, Energy Convers. Manag. 245 (2021) 114584, https://doi.org/10.1016/j.enconman.2021.114584.
[150] I. Dědek, S. Bartusek, J.J. Dvořáček, J. Nečas, J. Petruš, P. Jakubec, et al., Maximizing the electrochemical performance of supercapacitor electrodes from plastic waste, J. Energy Storage 72 (2023) 108660, https://doi.org/10.1016/j.est.2023.108660.
[151] A.M. Saleem, V. Desmaris, P. Enoksson, Performance enhancement of carbon nanomaterials for supercapacitors, J. Nanomater. 2016 (2016) 1–17, https://doi.org/10.1155/2016/1537269.
[152] C. Xuan, Z. Peng, J. Wang, W. Lei, K. Xia, Z. Wu, et al., Biomass derived nitrogen doped carbon with porous architecture as efficient electrode materials for supercapacitors, Chin. Chem. Lett. 28 (2017) 2227–2230, https://doi.org/10.1016/j.cclet.2017.09.009.
[153] Y.-J. Kim, J. Park, H. Kim, H.S. Jeong, J.H. Lee, S.M. Kim, et al., Simultaneous enhancement of mechanical and electrical properties of carbon nanotube fiber by infiltration and subsequent carbonization of resorcinol-formaldehyde resin, Composites, Part B 163 (2019) 431–437, https://doi.org/10.1016/j.compositesb.2018.12.132.
[154] H. Yi, K. Nakabayashi, S.-H. Yoon, J. Miyawaki, Pressurized physical activation: a simple production method for activated carbon with a highly developed pore structure, Carbon 183 (2021) 735–742, https://doi.org/10.1016/j.carbon.2021.07.061.
[155] D. Bergna, T. Varila, H. Romar, U. Lassi, Comparison of the Properties of Activated Carbons Produced in One-Stage and Two-Stage Processes 4 (2018) 41, https://doi.org/10.3390/c4030041. C.
[156] M.A.A. Zaini, L.L. Zhi, T.S. Hui, Y. Amano, M. Machida, Effects of physical activation on pore textures and heavy metals removal of fiber-based activated carbons, Mater. Today Proc. 39 (2021) 917–921, https://doi.org/10.1016/j.matpr.2020.03.815.
[157] M. Adibfar, T. Kaghazchi, N. Asasian, M. Soleimani, Conversion of poly(ethylene terephthalate) waste into activated carbon: chemical activation and characterization, Chem. Eng. Technol. 37 (2014) 979–986, https://doi.org/10.1002/ceat.201200719.
[158] S.-E. Chun, J.F. Whitacre, Formation of micro/mesopores during chemical activation in tailor-made nongraphitic carbons, Microporous Mesoporous Mater. 251 (2017) 34–41, https://doi.org/10.1016/j.micromeso.2017.05.038.
[159] E. Raymundo-Piñero, P. Azaïs, T. Cacciaguerra, D. Cazorla-Amorós, A. Linares-Solano, F. Béguin, KOH and NaOH activation mechanisms of multiwalled carbon nanotubes with different structural organisation, Carbon 43 (2005) 786–795, https://doi.org/10.1016/j.carbon.2004.11.005.
[160] J. Wang, S. Kaskel, KOH activation of carbon-based materials for energy storage, J. Mater. Chem. 22 (2012) 23710–23725, https://doi.org/10.1039/C2JM34066F.
[161] P. Rai, K.P. Singh, Valorization of Poly (ethylene) terephthalate (PET) wastes into magnetic carbon for adsorption of antibiotic from water: characterization and application, J. Environ. Manag. 207 (2018) 249–261, https://doi.org/10.1016/j.jenvman.2017.11.047.
[162] Y. Wen, X. Wen, K. Wenelska, X. Chen, E. Mijowska, Novel strategy for preparation of highly porous carbon sheets derived from polystyrene for supercapacitors, Diam. Relat. Mater. 95 (2019) 5–13, https://doi.org/10.1016/j.diamond.2019.03.015.
[163] S. Nanda, F. Berruti, Thermochemical conversion of plastic waste to fuels: a review, Environ. Chem. Lett. 19 (2021) 123–148, https://doi.org/10.1007/s10311-020-01094-7.
[164] R.-X. Yang, K. Jan, C.-T. Chen, W.-T. Chen, K.C.-W. Wu, Thermochemical conversion of plastic waste into fuels, chemicals, and value-added materials: a critical review and outlooks, ChemSusChem 15 (2022) e202200171, https://doi.org/10.1002/cssc.202200171.
[165] R. Chen, M. Yu, R.P. Sahu, I.K. Puri, I. Zhitomirsky, The development of pseudocapacitor electrodes and devices with high active mass loading, Adv. Energy Mater. 10 (2020) 1903848, https://doi.org/10.1002/aenm.201903848.

[166] R. Farzana, R. Rajarao, B.R. Bhat, V. Sahajwalla, Performance of an activated carbon supercapacitor electrode synthesised from waste Compact Discs (CDs), J. Ind. Eng. Chem. 65 (2018) 387–396, https://doi.org/10.1016/j.jiec.2018.05.011.
[167] T. Feng, S. Wang, Y. Hua, P. Zhou, G. Liu, K. Ji, et al., Synthesis of biomass-derived N,O-codoped hierarchical porous carbon with large surface area for high-performance supercapacitor, J. Energy Storage 44 (2021) 103286, https://doi.org/10.1016/j.est.2021.103286.
[168] D. He, W. Zhao, P. Li, S. Sun, Q. Tan, K. Han, et al., Bifunctional biomass-derived N, S dual-doped ladder-like porous carbon for supercapacitor and oxygen reduction reaction, J. Alloys Compd. 773 (2019) 11–20, https://doi.org/10.1016/j.jallcom.2018.09.141.
[169] J. Zhang, H. Chen, J. Bai, M. Xu, C. Luo, L. Yang, et al., N-doped hierarchically porous carbon derived from grape marcs for high-performance supercapacitors, J. Alloys Compd. 854 (2021) 157207, https://doi.org/10.1016/j.jallcom.2020.157207.
[170] X. Yuan, S. Li, S. Jeon, S. Deng, L. Zhao, K.B. Lee, Valorization of waste polyethylene terephthalate plastic into N-doped microporous carbon for CO2 capture through a one-pot synthesis, J. Hazard Mater. 399 (2020) 123010, https://doi.org/10.1016/j.jhazmat.2020.123010.
[171] J. Zhou, H. Shen, Z. Li, S. Zhang, Y. Zhao, X. Bi, et al., Porous carbon materials with dual N, S-doping and uniform ultra-microporosity for high performance supercapacitors, Electrochim. Acta 209 (2016) 557–564, https://doi.org/10.1016/j.electacta.2016.05.127.
[172] X. Cui, K. Tuo, H. Dong, X. Fu, S. Wang, N. Zhang, et al., Modification of phosphorus-doped carbon coating enhances the electrochemical performance of LiFe0.8Mn0.2PO4 cathode material, J. Alloys Compd. 885 (2021) 160946, https://doi.org/10.1016/j.jallcom.2021.160946.
[173] C. Liu, B.B. Koyyalamudi, L. Li, S. Emani, C. Wang, L.L. Shaw, Improved capacitive energy storage via surface functionalization of activated carbon as cathodes for lithium ion capacitors, Carbon 109 (2016) 163–172, https://doi.org/10.1016/j.carbon.2016.07.071.
[174] C. Zhao, J. Zheng, Y. Wang, P. Rui, G. Yang, C. Zhao, et al., Vaporized hydrothermal functionalization of carbon fiber and its superior supercapacitor performance, Energy Fuel. 36 (2022) 4052–4064, https://doi.org/10.1021/acs.energyfuels.2c00261.
[175] Y.N. Sudhakar, M. Selvakumar, D. Krishna Bhat, S. Karazhanov, Chandrabose R. Subash, Supercapacitor studies of activated carbon functionalized with poly (ethylene dioxythiophene): effects of surfactants, electrolyte concentration on electrochemical properties, Mater. Lett. 273 (2020) 127978, https://doi.org/10.1016/j.matlet.2020.127978.
[176] M. Abid Ma 'Azam, M.I. Radzi, M. Mupit, H. Osman, R.F. Munawar, K.F. Samat, et al., Cyclic voltammetry and galvanostatic charge-discharge analyses of polyaniline/graphene oxide nanocomposite based supercapacitor, Malays J Compos Sci Manuf 3 (2020) 14–26, https://doi.org/10.37934/mjcsm.3.1.1426.
[177] S. Banivaheb, V. Ghalandari, H. Smith, M.T. Reza, SolvX: solvothermal conversion of mixed waste plastics in supercritical toluene in presence of Pd/C catalyst, J. Environ. Chem. Eng. 10 (2022) 108622, https://doi.org/10.1016/j.jece.2022.108622.
[178] X. Hu, D. Ma, G. Zhang, M. Ling, Q. Hu, K. Liang, et al., Microwave-assisted pyrolysis of waste plastics for their resource reuse: a technical review, Carbon Resour Convers 6 (2023) 215–228, https://doi.org/10.1016/j.crcon.2023.03.002.
[179] M.P. Maniscalco, M. Volpe, A. Messineo, Hydrothermal carbonization as a valuable tool for energy and environmental applications: a review, Energies 13 (2020) 4098, https://doi.org/10.3390/en13164098.
[180] T. Helmer Pedersen, F. Conti, Improving the circular economy via hydrothermal processing of high-density waste plastics, Waste Manag. 68 (2017) 24–31, https://doi.org/10.1016/j.wasman.2017.06.002.
[181] Z. Zhao, L. Sun, Y. Li, W. Feng, Polymer-derived carbon materials for energy storage devices: a mini review, Carbon 210 (2023) 118066, https://doi.org/10.1016/j.carbon.2023.118066.
[182] Z. Xu, J. Wang, Z. Guo, F. Xie, H. Liu, H. Yadegari, et al., The role of hydrothermal carbonization in sustainable sodium-ion battery anodes, Adv. Energy Mater. 12 (2022) 2200208, https://doi.org/10.1002/aenm.202200208.
[183] V. Pavlenko, H.S. Khosravi, S. Żółtowska, A.B. Haruna, M. Zahid, Z. Mansurov, et al., A comprehensive review of template-assisted porous carbons: modern preparation methods and advanced applications, Mater. Sci. Eng. R Rep. 149 (2022) 100682, https://doi.org/10.1016/j.mser.2022.100682.
[184] J. Wang, W. Lv, Q. Ren, L. Yan, L. Zhang, Z. Shi, High-performance hard carbon anode prepared via an ingenious green-hydrothermal route, Appl. Surf. Sci. 558 (2021) 149824, https://doi.org/10.1016/j.apsusc.2021.149824.
[185] J. Liu, T. Yang, D.-W. Wang, G.Q. Lu, D. Zhao, S.Z. Qiao, A facile soft-template synthesis of mesoporous polymeric and carbonaceous nanospheres, Nat. Commun. 4 (2013) 2798, https://doi.org/10.1038/ncomms3798.
[186] A. Platek, C. Nita, C.M. Ghimbeu, E. Frąckowiak, K. Fic, Electrochemical capacitors operating in aqueous electrolyte with volumetric characteristics improved by sustainable templating of electrode materials, Electrochim. Acta 338 (2020) 135788, https://doi.org/10.1016/j.electacta.2020.135788.
[187] J. Liang, Z. Xiao, Y. Gao, X. Xu, D. Kong, M. Wagner, et al., Ionothermal strategy towards template-free hierarchical porous carbons for supercapacitive energy storage, Carbon 143 (2019) 487–493, https://doi.org/10.1016/j.carbon.2018.11.065.
[188] M. Baccour, N. Louvain, J.G. Alauzun, L. Stievano, P.H. Mutin, B. Boury, et al., Carbonization of polysaccharides in FeCl3/BmimCl ionic liquids: breaking the capacity barrier of carbon negative electrodes in lithium ion batteries, J. Power Sources 474 (2020) 228575, https://doi.org/10.1016/j.jpowsour.2020.228575.
[189] P. Kaur, G. Verma, S.S. Sekhon, Biomass derived hierarchical porous carbon materials as oxygen reduction reaction electrocatalysts in fuel cells, Prog. Mater. Sci. 102 (2019) 1–71, https://doi.org/10.1016/j.pmatsci.2018.12.002.
[190] H. Wu, T. Li, H. Li, D. Zhang, F. Xu, Sodium-storage performance of CuS microspheres with hydroxyl hyperbranched polyamide additive, Mater. Lett. 262 (2020) 127181, https://doi.org/10.1016/j.matlet.2019.127181.
[191] R. Ye, D.K. James, J.M. Tour, Laser-induced graphene, Acc. Chem. Res. 51 (2018) 1609–1620, https://doi.org/10.1021/acs.accounts.8b00084.
[192] A. Vashisth, M. Kowalik, J.C. Gerringer, C. Ashraf, A.C.T. van Duin, M.J. Green, ReaxFF simulations of laser-induced graphene (LIG) formation for multifunctional polymer nanocomposites, ACS Appl. Nano Mater. 3 (2020) 1881–1890, https://doi.org/10.1021/acsanm.9b02524.
[193] G.F. Hawes, D. Yilman, B.S. Noremberg, M.A. Pope, Supercapacitors fabricated via laser-induced carbonization of biomass-derived poly(furfuryl alcohol)/graphene oxide composites, ACS Appl. Nano Mater. 2 (2019) 6312–6324, https://doi.org/10.1021/acsanm.9b01284.
[194] J.E. Omoriyekomwan, A. Tahmasebi, J. Dou, R. Wang, J. Yu, A review on the recent advances in the production of carbon nanotubes and carbon nanofibers via microwave-assisted pyrolysis of biomass, Fuel Process. Technol. 214 (2021) 106686, https://doi.org/10.1016/j.fuproc.2020.106686.
[195] N. Saha, S. Banivaheb, M. Toufiq Reza, Towards solvothermal upcycling of mixed plastic wastes: depolymerization pathways of waste plastics in sub- and supercritical toluene, Energy Convers. Manag. X 13 (2022) 100158, https://doi.org/10.1016/j.ecmx.2021.100158.
[196] J. Wang, X. Li, T. Zhang, Y. Chen, T. Wang, Y. Zhao, Electro-reforming polyethylene terephthalate plastic to Co-produce valued chemicals and green hydrogen, J. Phys. Chem. Lett. 13 (2022) 622–627, https://doi.org/10.1021/acs.jpclett.1c03658.
[197] H. Zhou, Y. Ren, Z. Li, M. Xu, Y. Wang, R. Ge, et al., Electrocatalytic upcycling of polyethylene terephthalate to commodity chemicals and H2 fuel, Nat. Commun. 12 (2021) 4679, https://doi.org/10.1038/s41467-021-25048-x.
[198] G. Tang, W. Qiao, Z. Wang, F. Liu, L. He, M. Liu, et al., Waste plastic to energy storage materials: a state-of-the-art review, Green Chem. 25 (2023) 3738–3766, https://doi.org/10.1039/D2GC04927A.
[199] J. Choi, I. Yang, S.-S. Kim, S.Y. Cho, S. Lee, Upcycling plastic waste into high value-added carbonaceous materials, Macromol. Rapid Commun. 43 (2022) 2100467, https://doi.org/10.1002/marc.202100467.
[200] R. Mendoza-Carrasco, E.M. Cuerda-Correa, M.F. Alexandre-Franco, C. Fernández-González, V. Gómez-Serrano, Preparation of high-quality activated carbon from polyethyleneterephthalate (PET) bottle waste. Its use in the removal of pollutants in aqueous solution, J. Environ. Manag. 181 (2016) 522–535, https://doi.org/10.1016/j.jenvman.2016.06.070.
[201] Z. Chen, W. Wei, B.-J. Ni, H. Chen, Plastic wastes derived carbon materials for green energy and sustainable environmental applications, Environ Funct Mater 1 (2022) 34–48, https://doi.org/10.1016/j.efmat.2022.05.005.
[202] S.L. Chiam, H.N. Lim, S.M. Hafiz, A. Pandikumar, N.M. Huang, Electrochemical performance of supercapacitor with stacked copper foils coated with graphene nanoplatelets, Sci. Rep. 8 (2018) 3093, https://doi.org/10.1038/s41598-018-21572-x.
[203] J.P. Jyothibasu, R.-H. Lee, Green synthesis of polypyrrole tubes using curcumin template for excellent electrochemical performance in supercapacitors, J. Mater. Chem. A 8 (2020) 3186–3202, https://doi.org/10.1039/C9TA11934E.

[204] S. Sagadevan, A.R. Marlinda, MohdR. Johan, A. Umar, H. Fouad, O.Y. Alothman, et al., Reduced graphene/nanostructured cobalt oxide nanocomposite for enhanced electrochemical performance of supercapacitor applications, J. Colloid Interface Sci. 558 (2020) 68–77, https://doi.org/10.1016/j.jcis.2019.09.081.
[205] L. Wang, Q. Zeng, Q. Chen, C.M. Li, J. Chen, Synergistically boosting the electrochemical performance of polypyrrole-coated activated carbon derived from carbon dots for a high-performance supercapacitor, Chem. Commun. 57 (2021) 9264–9267, https://doi.org/10.1039/D1CC02823E.
[206] L.L. Zhang, X.S. Zhao, Carbon-based materials as supercapacitor electrodes, Chem. Soc. Rev. 38 (2009) 2520–2531, https://doi.org/10.1039/B813846J.
[207] O. Gharbi, M.T.T. Tran, B. Tribollet, M. Turmine, V. Vivier, Revisiting cyclic voltammetry and electrochemical impedance spectroscopy analysis for capacitance measurements, Electrochim. Acta 343 (2020) 136109, https://doi.org/10.1016/j.electacta.2020.136109.
[208] E. Sadeghi, M.M. Gholami, M. Hamzeh, S.M.M. Alavi, M. Saif, A systematic overview of power electronics interfaced electrochemical impedance spectroscopy for energy storage systems, J. Energy Storage 62 (2023) 106850, https://doi.org/10.1016/j.est.2023.106850.
[209] N. Ma, D. Yang, S. Riaz, L. Wang, K. Wang, Aging mechanism and models of supercapacitors: a review, Technologies 11 (2023) 38, https://doi.org/10.3390/technologies11020038.
[210] T. Zhang, B. Fuchs, M. Secchiaroli, M. Wohlfahrt-Mehrens, S. Dsoke, Electrochemical behavior and stability of a commercial activated carbon in various organic electrolyte combinations containing Li-salts, Electrochim. Acta 218 (2016) 163–173, https://doi.org/10.1016/j.electacta.2016.09.126.
[211] U. Samukaite-Bubniene, A. Valiūnienė, V. Bucinskas, P. Genys, V. Ratautaite, A. Ramanaviciene, et al., Towards supercapacitors: cyclic voltammetry and fast Fourier transform electrochemical impedance spectroscopy based evaluation of polypyrrole electrochemically deposited on the pencil graphite electrode, Colloids Surf. A Physicochem. Eng. Asp. 610 (2021) 125750, https://doi.org/10.1016/j.colsurfa.2020.125750.
[212] B.M. Hryniewicz, R.V. Lima, L.F. Marchesi, M. Vidotti, Impedimetric studies about the degradation of polypyrrole nanotubes during galvanostatic charge and discharge cycles, J. Electroanal. Chem. 855 (2019) 113636, https://doi.org/10.1016/j.jelechem.2019.113636.
[213] X. Yun, B. Lu, Z. Xiong, B. Jia, B. Tang, H. Mao, et al., Direct 3D printing of a graphene oxide hydrogel for fabrication of a high areal specific capacitance microsupercapacitor, RSC Adv. 9 (2019) 29384–29395, https://doi.org/10.1039/C9RA04882K.
[214] H. Shi, Activated carbons and double layer capacitance, Electrochim. Acta 41 (1996) 1633–1639, https://doi.org/10.1016/0013-4686(95)00416-5.
[215] S. Kumagai, R. Yamasaki, T. Kameda, Y. Saito, A. Watanabe, C. Watanabe, et al., Aromatic hydrocarbon selectivity as a function of CaO basicity and aging during CaO-catalyzed PET pyrolysis using tandem μ-reactor-GC/MS, Chem. Eng. J. 332 (2018) 169–173, https://doi.org/10.1016/j.cej.2017.09.077.
[216] M. Domingo-García, J.A. Fernández, M.C. Almazán-Almazán, F.J. López-Garzón, F. Stoeckli, T.A. Centeno, Poly(ethylene terephthalate)-based carbons as electrode material in supercapacitors, J. Power Sources 195 (2010) 3810–3813, https://doi.org/10.1016/j.jpowsour.2009.12.090.
[217] S. Chen, S. Fang, A.I. Lim, J. Bao, Y.H. Hu, 3D meso/macroporous carbon from MgO-templated pyrolysis of waste plastic as an efficient electrode for supercapacitors, Chemosphere 322 (2023) 138174, https://doi.org/10.1016/j.chemosphere.2023.138174.
[218] D.N. Sangeetha, M.S. Santosh, M. Selvakumar, Flower-like carbon doped MoS2/Activated carbon composite electrode for superior performance of supercapacitors and hydrogen evolution reactions, J. Alloys Compd. 831 (2020) 154745, https://doi.org/10.1016/j.jallcom.2020.154745.
[219] N. Alhokbany, J. Ahmed, M. Ubaidullah, S. Mutehri, M.A.M. Khan, T. Ahamad, et al., Cost-effective synthesis of NiCo2O4@nitrogen-doped carbon nanocomposite using waste PET plastics for high-performance supercapacitor, J. Mater. Sci. Mater. Electron. 31 (2020) 16701–16707, https://doi.org/10.1007/s10854-020-04224-7.
[220] N.A. Elessawy, J. El Nady, W. Wazeer, A.B. Kashyout, Development of high-performance supercapacitor based on a novel controllable green synthesis for 3D nitrogen doped graphene, Sci. Rep. 9 (2019) 1129, https://doi.org/10.1038/s41598-018-37369-x.