Waste Management 171 (2023) 71–85

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Research Paper

Sustainable energy and waste management: How to transform plastic waste into carbon nanostructures for electrochemical supercapacitors

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ARTICLE INFO

Keywords:
Plastic waste
Sustainability
Carbon
Pyrolysis
Energy storage
Supercapacitors

ABSTRACT

Plastic waste consumption increases exponentially every year, mainly in the last three years due to the COVID-19 pandemic. The rapid growth of plastic products has exceeded the world's capacity to deal with this type of trash. Thus, it has become a substantial environmental concern in modern society. Another dire concern is the improper disposal of used supercapacitors, leading to serious environmental impacts. Consequently, critical action to tackle this issue is to transform trash into high-valued materials, such as carbon nanomaterial supercapacitors. Considering several methodologies of recycling, pyrolysis stands out due to its simplicity and easy handling of mixed plastic waste to produce carbonaceous materials with different dimensions (0, 1, 2, and 3D). Thus, from this technology, it is possible to create new opportunities for using plastic waste and other types of waste to produce cheaper carbon-based materials for supercapacitors. This review aims to provide readers with a sustainability-driven view regarding the reutilization of plastic trash, discusses the environmental consequences of not doing so, and shows plastic waste solutions. Despite the broad scope of the topic, this review focuses on identifying the currently studied strategies to convert plastic waste into carbon-based electrodes, using less expensive and more efficient competitive protocols, besides emphasizing the diverse types (0, 1, 2, and 3D) of nanostructures. This review also proposes promising options for a sustainable cycle of plastic waste and supercapacitor.

1. Introduction

Post-consumer synthetic polymers have become one of the main threats to the world due to growing pollution rates. Currently, discarded plastic is an undesirable ecological disaster, including zone layer depletion and climate change Cañado et al. (2022). According to the Organization for Economic Co-operation and Development (OECD), only 9% of plastic waste is recycled, 50% ends up in landfills, and 22% goes to uncontrolled dumpsites or is discarded in aquatic or terrestrial environments OECD, (2022).

In the last three years, the COVID-19 pandemic has led to a significant increase in single-use plastic. As a result, an unprecedented amount of single-use plastic from hospitals and households has been discarded in landfills. Most of it reaches the ocean, further damaging the ecosystem. This substantial rise in trash production is a warning to stakeholders and organizations. Indeed, plastic management is critically needed, and governments and scientists need to combat the local- and global-scale plastic waste calamity Fagnani et al. (2021).

As an alternative to reduce the serious threat of plastic waste to the environment, numerous chemists who synthesize polymers have been doing extensive research aiming to develop platforms for manufacturing sustainable polymers Abd-El-Aziz et al. (2020); Scott, (2000); Utetiwabo et al. (2020). Nevertheless, this option alone is not sustainable, not to mention that it does not cover an enormous quantity of previously

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https://doi.org/10.1016/j.wasman.2023.08.028
Received 12 January 2023; Received in revised form 23 July 2023; Accepted 23 August 2023

wasted synthetic and non-biodegradable polymers. Some technical solutions are currently employed to solve this issue, including mechanical recycling, chemical recycling (pyrolysis, gasification, solvolysis, depolymerization), and incineration Yang et al. (2022).

Incineration and mechanical recycling are extenuating strategies still not used to the fullest Scott, (2000). Scientists have put their efforts into transforming the modern industry by promoting chemical recycling. Chemical recycling by a closed loop is ideal for retaining material excellence. Regarding the waste hierarchy, it has been stated that pyrolysis is the most widely used thermal remediation method because of its simplicity, low price, and relatively small footprint compared to other treatment methods. Given the capacity of commodity polymers, chemical recycling that reuses plastic waste is a serious and highly relevant topic Report, (2020).

From the technological point of view, plastic wastes are enriched carbon sources, making them excellent candidates for carbon nanomaterial synthesis Zhuo and Levendis, (2014). Accordingly, many recycling techniques can transform carbon-rich precursors into various carbon materials. However, pyrolysis stands out Ravi and Vadukumpully, (2016). Different nanostructures (0, 1, 2, and 3D) can be synthetized from carbonaceous materials. Carbon nanostructures belong to a versatile material class that has been extensively used in different research fields, including biological E. H. Fragal et al. (2020), technological Fragal et al. (2019), environmental, and energy storage demands Fragal et al. (2021); V. H. Fragal et al. (2020).

Driven by the growing demand for renewable energy, the supercapacitor market has heated up in recent years. Supercapacitors are currently used in regenerative braking systems. Their high-power density allows them to quickly store and unload power, which helps gather energy generated by car brakes. Unlike energy storage in chemicals, supercapacitors keep electricity in a static state. Since they need more physical than chemical systems, supercapacitors do not decay as quickly as do lithium-ion batteries. This represents a preeminent perspective in terms of increasing the durability of electric vehicles Noori et al. (2019). Most supercapacitor applications are not taken into consideration due to high production costs. Electrode costs can reach 50% of the price of a supercapacitor. Carbon-based supercapacitors promise excellent cost–benefit ratios for power systems regarding economic and sustainability aspects. This storage device supplies electrical energy between an adsorbed electrolyte layer and the carbonaceous electrode surface. The cost of electrodes could be reduced due to these materials, allowing supercapacitors to become low-cost energy storage devices Utetiwabo et al. (2020).

In the present review, the *status quo* on sustainable recycling routes to transform plastic waste into carbonaceous nanostructures for energy storage applications is reviewed and discussed. The crescent number of recent works highlights the importance of this subject, whereas the justification for its relevance is placed on the environmental and technological impacts. The consumption of plastic waste for carbon material production minimizes the harmful effects of plastic residues on the environment and provides a profitable approach for producing electrodes to be used in supercapacitors. Some review papers on converting waste into carbon have already been published Bhat et al. (2023); Tatrari et al. (2021); Utetiwabo et al. (2020). Utetiwabo et al. (2020) introduced many examples of industrial and plastic waste that can be transformed into carbon electrodes. Tatrari et al. (2021) reviewed the literature emphasizing the production of carbon nanomaterials from solid wastes to be used in supercapacitors. In the most recent work, Bhat et al. (2023) brought new perspectives to using different wastes to produce carbon for supercapacitors. However, a more comprehensive view of the nanostructure-property relationship of carbon nanomaterials and the reuse of discarded used supercapacitors would be of general interest to the field. The methodologies explored for converting plastic waste into carbon materials are deeply examined to fill the existing knowledge gap. Looking into the obtained nanostructures, it is discussed how those nanostructures are formed and how they affect the energy storage properties. The double layers capacitance that arises from the formed nanostructures are carefully examined and compared.

Additionally, strategies for recycling a supercapacitor after the end of its life are also analyzed. An overview of how to transform trash into carbon electrodes for electrochemical supercapacitors is also discussed. A short introduction to electrochemical supercapacitors, including their different components, is presented. Lastly, the advances, challenges, and future trends for sustainability regarding supercapacitors are greatly discussed. We believe that this paper will contribute to the waste valorization field, providing the most up-to-date information about solutions to convert trash into sustainable carbon electrodes for supercapacitors.

1.1. *Methodology of the review*

An analysis of relevant publications published over the last 10 years was steered to comprehend the developments in the research area of plastic waste management for supercapacitor applications. In the first part of this paper, the analysis focuses on the environmental and economic impact of the disposal of single-use plastics, highlighting the consequences of the COVID-19 pandemic for the environment. In the second part, we search for methodologies for managing plastic waste and its destination. In the third part, the search focused on synthesis methods for transforming carbon derived from plastic waste into electrodes for supercapacitors. Finally, research was conducted to cover the reuse and recycling of used supercapacitors.

The analysis was conducted using the Scopus scientific database to reach these goals. The authors selected Google Scholar, Web of Science, Research Gate, and Scopus, limiting the search from 2014 to 2023. A search was achieved using the following terms in the title or keywords:

- “Environmental” and “economic” impact of “plastic” or “polymer” waste
- “Recycling”, “plastic”, or “polymer”
- “Carbon materials” of “plastic” or “polymer” for supercapacitors
- “Carbon nanostructures for supercapacitors”
- “Reuse” and/or “recycling” of supercapacitors

Articles published in high-impact journals on using plastic waste and interesting synthesis methods, plastic waste sources, and electrochemical performance are highlighted in this work. This analysis was not intended to cover all articles corresponding to the search terms but to demonstrate the perspective of the main improvements in the energy storage field through plastic waste recycling.

2. Plastic waste: General impact and a sustainable view

Plastics are often non-biodegradable polymers, indispensable in modern life. They are used for several purposes, which include building materials, packaging, vehicles, medical devices, protection of foodstuffs, etc. In a nutshell, plastics are used to improve the quality of life of billions of people. They are durable and lightweight, which allows a reduction in the weight of cars, aircraft, packaging, and piping. Besides being versatile, for they can be used for the most diverse purposes, plastic materials also bring benefits related to sustainability.

However, it is worth remembering that the plastics life cycle is composed of raw material extraction; design and production; packing and distribution; use and maintenance; and recycling, reuse, recovery, or final disposal. Consequently, excessive use of polymers leads to vast waste, impacting the ecosystem, health, and economy Wilts et al. (2019). Plastic waste has been a primary environmental and economic concern for a long time. Since the 1950s, plastic production has grown faster than any other material, such as ceramics and metals. Researchers estimate that, since the early 1950s, more than 8.3 billion tons of plastic have been cumulatively produced Geyer et al. (2017). About two-thirds of this amount, 6.3 billion tons, has been turned into garbage, while 2.6 billion tons is still being used. Around 60% of all plastic waste is in landfills or natural environments Geyer et al. (2017).

The COVID-19 pandemic had a direct impact on plastic industrialization. Premature deaths and the extended lockdown imposed by governments disrupted the supply chain, impairing many factories and reducing their productivity Zhou et al. (2021). Conversely, the pandemic created a considerable demand for single-use plastics, mainly those used in hospitals as personal protective equipment or to treat patients, such as syringes, masks, gloves, face shields, COVID tests, and covering for clothing. In addition, many people were forced to stay at home, which increased the demand for food delivery and, consequently, packaging consumption. Packaging, by far, represents the largest end-use market, usually made for single-use applications. Thus, during the two years of the pandemic, human activity generated extra plastic waste on the planet beyond what was expected. In their review, Klemeš et al. (2020) discuss the impact of the COVID-19 pandemic on raising plastic waste.

Meanwhile, the end of the journey of plastic waste derived from fossil sources continues undefined and corresponds to an emergent research field. For the moment, the correct administration of plastic waste is necessary. Nowadays, there are three destinations for post-consumer plastic: i) landfills; ii) incineration; and iii) recycling Zhao et al. (2020). Discarding plastic waste in landfills is considered harmful, for it contaminates the soil and water bodies. Besides that, dumps should occupy a specific area Plastic Europe, (2021).

On the other hand, incineration is a positive method, as it reduces the number of landfills. However, hazardous substances are released during the procedure Zhao et al. (2020). According to European Bioplastics, incineration is the second-best option for plastic waste management after mechanical, chemical, biological, and organic recycling Dilkes-Hoffman et al. (2019).

Unlike other management methods, recycling causes fewer environmental effects, as it maximizes the lifespan of plastic. Thus, recycling is perhaps the top management strategy for the plastics crisis. Even so, only a fraction of all plastic used is recycled on Earth Zhao et al. (2020).

Remarkable efforts have been made to lessen the quantity of plastic waste generated annually. However, they are still insufficient to address the persistent yearly increase in plastic waste. Regrettably, the increase in recycling and reuse of plastics is considerably inferior to the production growth rate. Only 9% percent of the total plastic waste in the biosphere was recycled in 2020 Parker, (2018).

Plastic waste can take many centuries to degrade entirely under natural environmental conditions Parker, (2018). Consequently, it affects air quality (open dumps) and local flooding caused by drain clogging. Moreover, it eventually reaches the oceans when poorly managed, polluting the natural environment Li et al. (2016). Every year, millions of tons of plastic are wasted around the Earth. Approximately 2.7×10^5 tons of plastic affect marine animals Plastic Europe, (2021).

The effect of plastic pollution on human life is evident. Plastic from the aquatic ecosystem, which fish ingest, also harms human health if these fish are consumed Khalid et al. (2021). Thus, due to chemical bioaccumulation, humans are exposed to plastic particles via seafood consumption, which may cause adverse health issues Wright and Kelly, (2017).

Accordingly, plastic factories have been pressured to implement sustainable recycling and reuse principles. Environmental protection agencies have imposed regulations on the plastics industry to monitor, execute, and report sustainability activities European Commission, (2018). The characteristics of plastic that make it so useful – durability and resistance to degradation – also make it too stable to be decomposed entirely by natural processes. Most plastic will never totally disappear. It gets smaller and smaller, until it becomes what is called microplastics Gola et al. (2021).

3. Waste to carbon materials: Recycling process

Plastic waste recycling can be divided into mechanical and chemical methods Jeswani et al. (2021). The first type of process is most used for poly(ethylene terephthalate) (PET) and high-density polyethylene (HDPE). It has a substantial disadvantage, that is, degrading the mechanical properties of materials. Instead, the chemical process comprises the depolymerization of the backbone chain of plastics into mixtures of monomers and oligomers, which should be recovered in a novel plastic synthesis.

Currently, chemical recycling is considered by the industry as the 'Holy Grail.' As previously mentioned, chemical recycling can break down the polymer network into valuable feedstocks for the chemical industry, such as monomers, oligomers, or both Atia et al. (2014); de Castro et al. (2009), re-manufacturing plastic without losing its properties Fávaro et al. (2013); Nunes et al. (2014); Souza et al. (2020). Fig. 1**a** demonstrates the circular plastic process, from production to recycling. It is worth noting that chemical recycling is crucial in this big puzzle. Besides converting the bulk material into its components, it can supply fuel and energy Jeswani et al. (2021).

In recent years, sustainable research has aimed to transform waste into valuable products, such as carbon functional material for supercapacitors Al-Enizi et al. (2020). Thus, it is likely that two global concerns will be overcome: plastic pollution and the energy crisis. To transform trash into valuable material, generally, chemical recycling is the alternative. Different procedures are used to recycle plastic waste, namely solvent-based, thermochemical, and enzymolysis. Each one of these procedures has a particular goal. Thermochemical methods are frequently used to transform plastic waste into carbon functional materials for supercapacitors. They comprise pyrolysis and gasification/hydrogenation (Fig. 1**b**). Pyrolysis is operated in inert conditions, generating liquids and gaseous fuel, besides solid char, with significant economic importance. In addition, the process parameters can be adjusted to obtain the desired end products Miandad et al. (2019).

Pyrolysis is a successful technique to manufacture carbon materials from plastic waste. The method can be performed within a large range of temperatures, from low (room or lesser) to high (1000 °C or even higher), providing the highest carbon yields Deng et al. (2016). Another advantage of this technique is the use of catalysts. In addition, porosity and specific surface area, essential characteristics of carbon nanostructures, can be coordinated by adjusting pyrolysis parameters Deng et al. (2016). However, the procedure is still expensive, and some plastic waste needs a further step (chemical or physical activation) to be altered into functional carbons.

These further steps comprise physical and chemical activation. As mentioned before, structures with many pores and a large surface area are desirable carbon characteristics for supercapacitor applications. Under this circumstance, activation is a key step to reaching this goal. Physical activation usually occurs after pyrolysis of plastic waste at a high temperature which can reach 1000 °C in a carbon dioxide or steam atmosphere. Meanwhile, chemical activation using specific chemical compounds, such as acids, bases, or salts, is required Sajjadi et al. (2019). The chemicals are pore-forming agents in this process and can become active during or after pyrolysis. When used before, the activating agent is embedded into a carbon precursor and then annealed at a high-temperature Ma et al. (2017). Physical activation is considered an eco-friendly method since it does not require chemicals. However, chemical activation is the method that researchers most use to create carbon functional materials derived from plastic waste for supercapacitor applications Nahil and Williams, (2012); Sarıcı-Özdemir and Önal, (2018).

From the economic and environmental point of view, pyrolysis has some technical challenges, including, but not limited to, the availability, selection, pre-treatment, and toxicity of feedstock Qureshi et al. (2020). Pyrolysis requires high-quality feedstock, and plastics collected from different wastes are very heterogeneous. Thus, it is necessary to select plastic waste for the process. For example, the degradation of PET and PVC leads to the formation of subproducts that deteriorate the equipment, contaminating the products and emitting hazardous gases Qureshi

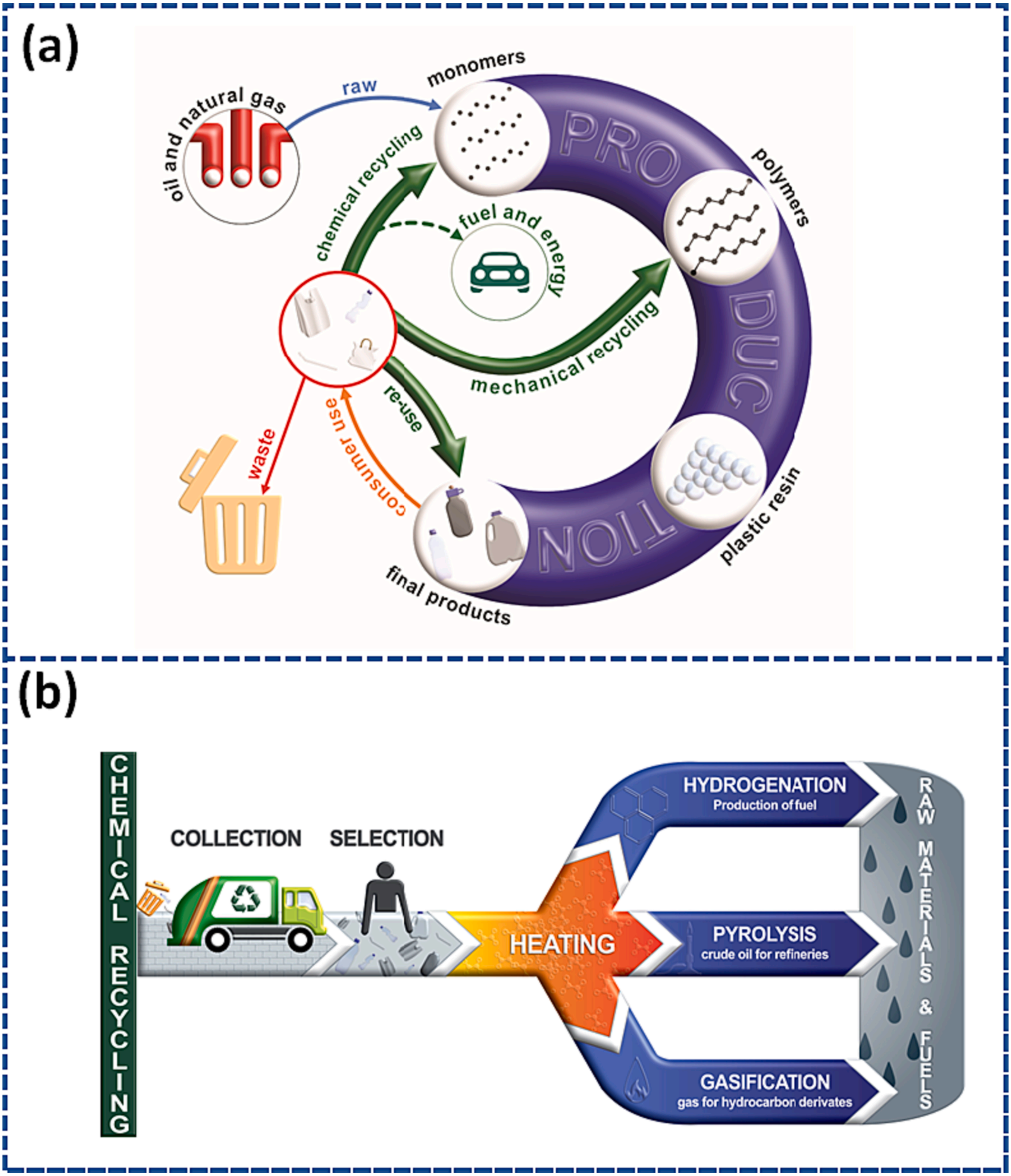

Fig. 1. **(a)** Schematic steps in production and recycling of plastics. **(b)** scheme of chemical recycling and its main thermochemical recycling methods and products.

et al. (2020).

On the other hand, pyrolysis processes consume a lot of energy, which causes an increase in harmful environmental effects. Regarding sustainability, pyrolysis is a valuable technique to convert plastic waste into carbon-value added materials, reducing the use of non-renewable resources. Recycling through the circular economy is more sustainable than producing new plastics. The key role of the pyrolysis method becomes significant when a product gets to the end of its life Dharmaraj et al. (2021); Jeswani et al. (2021).

A good review article published recently has demonstrated the role of pyrolysis from the circular economy point of view and its environmental and social effects Andooz et al. (2023). This shows that even with some limitations, the excellent advantages surpass the disadvantages, and pyrolysis is, to date, the most useful technique used in different countries and the base process for obtaining different carbon nanostructures Deng et al. (2016).

Despite there being some negative points about thermal treatment, more benefits are founded in recycling plastic for the long term and their utilization in supercapacitor design. Considering different types of plastics, their conversion into carbon is an alternative to reduce the serious problem of plastic waste to the environment, reducing the cost of supercapacitor production. Also, the eco-friendly electrodes in supercapacitors could present electrochemical properties superior to not eco-friendly electrodes.

An interesting example of how the recycling procedure reduces both plastic waste and the cost of supercapacitor production and even presents better electrochemical performance is demonstrated in the Wuamprakhon et al. (2022) work. Recycling poly(lactic acid) (PLA) from industrial waste presents a change of view in plastic waste recycling for supercapacitor platforms. PLA used as filament can reach capacitance values 75 times higher than commercially available conductive PLA filaments at the cost of £0.15 per electrode Wuamprakhon et al. (2022). The process is based on blending PLA, carbon black, and polyethylene glycol in a chamber (170 °C), being a new direction for plastic waste recycling based on a simple, environmentally economical treatment method with a low energy-consuming process.

4. Carbon-based nanostructures derived from plastic waste for supercapacitor application

4.1. Background to electrochemical supercapacitors

The increasing expansion of the energy sector has imposed the necessity to develop more effective energy storage technologies, like supercapacitors, to improve efficiency. Supercapacitors are energy storage devices with fast charge and discharge due to their low resistance Shi et al. (2020). They can provide higher energy density compared to traditional capacitors and higher power density compared to batteries, which are the most used system nowadays Funabashi, (2016).

Supercapacitors are used in several sectors, such as transportation, power backup, local and portable electronics, biomedical, etc. However, photovoltaic solar cells, solar light, and electric vehicles are pivotal targets for supercapacitor applications. Supercapacitors can be subdivided into electric double-layer (EDLCs), pseudocapacitors, and hybrid capacitors (Fig. 2).

Briefly, EDLCs form electric double layers on the electrodes' surface. The double layers are formed by aligning ions and electrons at the border between electrodes and electrolytes. These phenomena are responsible for the capacitance of this type of supercapacitor. EDLCs are typically based on electrodes with an excellent surface area, such as carbon materials V. H. Fragal et al. (2020). On the other hand, in pseudocapacitors, capacitance derives from a fast and reversible faradaic procedure due to electroactive materials, including conductive polymers, metal oxides, etc. Finally, hybrid capacitors combine EDLCs and pseudocapacitors Muzaffar et al. (2019). The synergic effect of materials is accountable for the better performance of hybrid supercapacitors Zhou et al. (2018).

Despite the excellent properties, many challenges limit the growth of the supercapacitor market, such as the high price of producing the electrode Utetiwabo et al. (2020). As an alternative, several scientists have dedicated attention to producing electrodes based on carbon materials for energy storage devices. Different structures, including activated carbon, mesoporous and microporous carbon, nanotubes, nanofibers, and graphene, have shown excellent electrocatalytic performance. In addition, they can also be used as a template to produce materials with different morphologies Li et al. (2020).

As electrodes for supercapacitors, the key roles of carbon are: (i) increasing electrical conductivity; (ii) decreasing charge transfer resistance; (iii) ensuring stability during the charge–discharge cycle; (iv) preventing structural pulverization; and (v) inhibiting mutual aggregation Pandolfo and Hollenkamp, (2006). Accordingly, carbon-based materials need a combination of properties, including high conductivity, stability, porosity, surface area, and low-cost V. H. Fragal et al. (2020). Low cost is achieved by using sustainable sources, like plastic waste, which can be easily shaped according to the production method in question.

In addition, carbon materials can be processed and functionalized to make them appropriate for hybrid supercapacitor applications. The intrinsic ability to process a composite containing inorganic materials has boosted the visibility of carbon with commercial value. For these reasons, it is indispensable to present an efficient, cheap, accessible, and sustainable route to produce carbon supercapacitors. Hence, as mentioned in previous sections, transforming plastic waste into carbon materials for electrodes in supercapacitors is an outstanding alternative to reduce plastic waste production and overcome the plastic energy crisis.

4.2. State of the art in carbon-based nanostructures derived from plastic waste for supercapacitor applications

The pyrolysis method has been the base technology to prepare carbon nanostructures for supercapacitor applications Kumar et al. (2021); Machado et al. (2021). From this technology, plastic waste can be converted into carbonaceous materials to produce zero-, one-, two-, and three-dimensional nanostructures (Fig. 3). The different dimensionality of carbon material can modulate the electrochemical performance of a device. Also, different spatial dimensions combine characteristics that

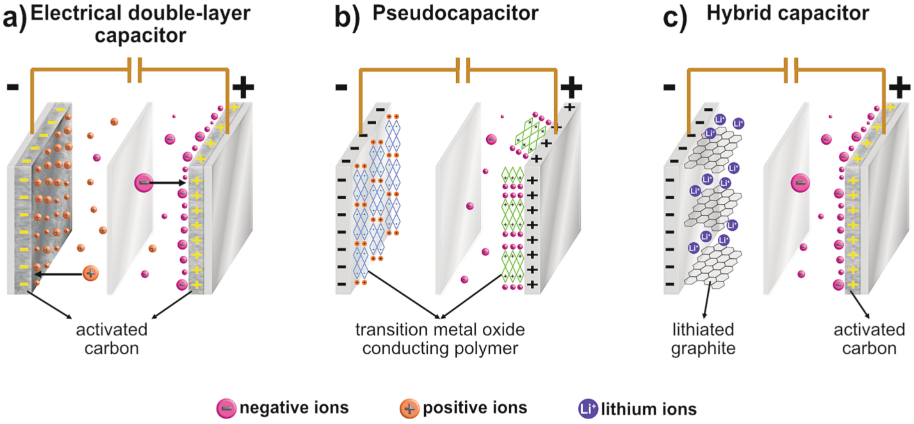

Fig. 2. Schematic representation of (a) electrical double-layer capacitor; (b) pseudocapacitor; and (c) hybrid capacitors.

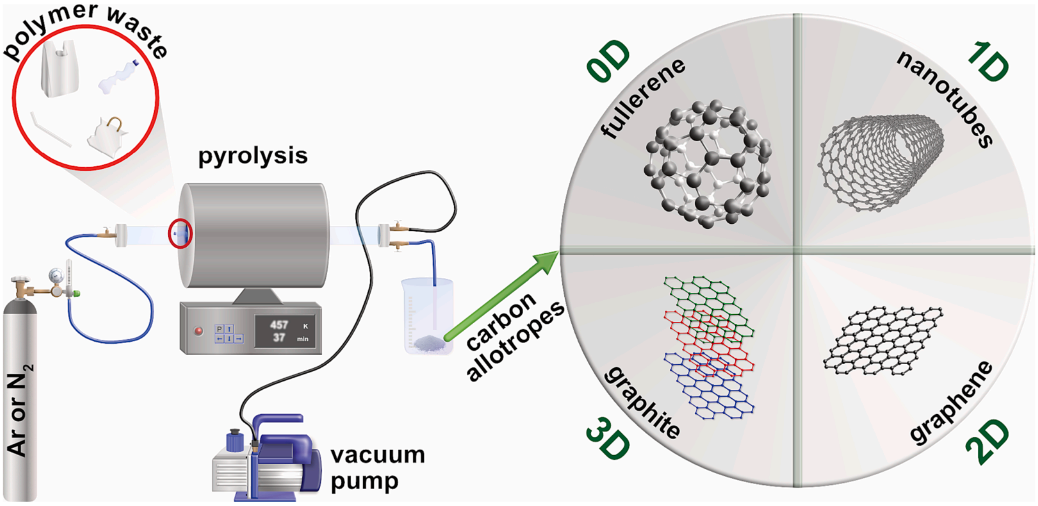

Fig. 3. Scheme of the most used method (pyrolysis) to convert polymer waste into 0D-3D carbon materials.

make these nanostructures highly desirable for energy applications Zheng et al. (2020).

4.2.1. *Zero-dimensional (0D) carbon nanomaterials*

The zero-dimensional (0D) carbon nanomaterials are distinct because their dimensions are measured within the nanoscale, specifically between 1 and 100 nm. Nevertheless, diameters up to 1 μm are still considered a part of this class due to the beneficial results produced by their small size. Carbon quantum dots (C-QD), carbon nanoparticles, and nanospheres are the most representative of 0D carbon nanomaterials Zheng et al. (2020).

C-QD nanomaterials as electrodes offer unique features to provide high-performance supercapacitors. They possess exceptional physical and chemical properties, such as a large surface area, an extraordinary ability to be easily integrated with several nanomaterials, significant edge effects, low toxicity, and outstanding electron transfer/reservoir performance Ji et al. (2020); Liu et al. (2013). Carbon nanospheres show fast ionic transportation and high structural stability, which are highly desirable features for supercapacitors. Nevertheless, the main disadvantage of 0D materials is their easy aggregation, which occurs spontaneously ($\Delta G < 0$), leading to a significant decrease in total area.

Carbon nanospheres derived from plastic waste are well-known as promising candidates for supercapacitors. Jiang et al. (2014) found a proper pathway to recycle plastic waste. The authors transformed polytetrafluoroethylene (PTFE) into carbon nanospheres. They used the pyrolysis method and calcium carbonate ($CaCO_3$) as a hard template to produce nanoporous carbon spheres: Carbon-2:1, where 2: 1 is the PTFE: $CaCO_3$ mass ratio. The carbon structure was further doped with nitrogen using urea as a precursor in a mass ratio of $CaCO_3$: $CO(NH_2)_2$ of 1: 2 to improve the electrochemical property (Carbon-2:1:2). $CaCO_3$ is an important agent to produce hollow carbon spheres, as demonstrated through FESEM (Fig. 4**a–c**) and HRTEM images (Fig. 4**b–d**) Jiang et al. (2014).

It was also shown that the presence of N atoms in the carbon structure plays an important role in improving the specific surface area that raised from 646.3 to 1048.2 m^2/g after doping. The hollow carbon nanosphere doped with N atoms as an electrode showed superior capacitance of 237.8F/g at 1 A/g (Fig. 4**e and f**) Jiang et al. (2014). In addition, it showed an excellent cyclability rate, keeping 97.6% of its capacitance after 10,000 cycles (Fig. 4**g and h**) Jiang et al. (2014). By benefiting from the presence of N atoms in the structure, the as-measured elevated specific surface area was favorable to enhancing ion mobility and wettability of the electrode surface by the presence of an electrolyte. All these experimental parameters contributed to improving the performance of the active material.

Despite the characteristics of 0D carbon nanomaterials, there are only a few studies about 0D carbon derived from polymer waste for supercapacitors. Furthermore, most reports address natural polymer waste (biowaste), mainly for carbon dots.

4.2.1.1. One-dimensional (1D) carbon nanomaterials. Materials known as 1D nanomaterials possess just one dimension outside the nanoscale. Subsequently, the finding of carbon nanotube 1D nanomaterials has been drawing great attention in different fields of nanotechnology, mainly in energy storage Kumar et al. (2021). Polymer waste-derived 1D carbon nanomaterials can be classified by their different morphology, e.g., carbon nanotubes (CNTs) and carbon nanofibres (CNFs). These structures have a large surface area, high tensile strength, and oriented growth direction, allowing for fast electron and ion transportation, which is considered an ideal property for an excellent performance of energy storage systems Kumar et al. (2021).

CNTs are formed by sp^2-hybridized bonding with graphene sheets wrapped around them Vairavapandian et al. (2008). These structures possess exceptional properties, such as superior mechanical and thermal properties, specific electronic properties, and tensile strength 100 times higher than that of stainless steel Belin and Epron, (2005); Williams, (2021). The properties mentioned above make this structure a candidate for the next generations of electrode designs. For instance, Abbas et al. (2021) investigated the electrochemical properties of multi-walled carbon nanotubes (MWCNTs) produced from flexible plastic packaging. The authors used a three-step procedure involving pyrolysis, catalytic cracking, and condensation. Sources of plastic waste are composed of different polymers, such as PET (11.8%), polyethylene (PE, 53%), polyamide (PA, 1.3%), and polypropylene (PP, 28.2%). The 1D structure was functionalized, and the electrochemical performance was evaluated. The as-obtained functionalized MWCNTs showed the best capacitive performance compared to the other samples, including the commercial MWCNTs Abbas et al. (2021).

CNFs derived from plastic waste have been used successfully as supercapacitor electrodes. Like CNTs, CNFs, which are normally produced using electrospinning and further through pyrolysis, have a large surface area with tunable porosity, a high aspect ratio, good mechanical properties, and good electrical conductivity, which makes them a good choice for energy storage devices (Gopalakrishnan et al., 2018). Electrospinning is a multipurpose and low-cost method that produces large amounts of flexible nanofibers. In addition, the process can generate mats with controllable morphology Gopalakrishnan et al. (2018); Oliveira et al. (2020). For instance, CNFs were made by electrospinning followed by carbonization using waste polystyrene (PS) foam as

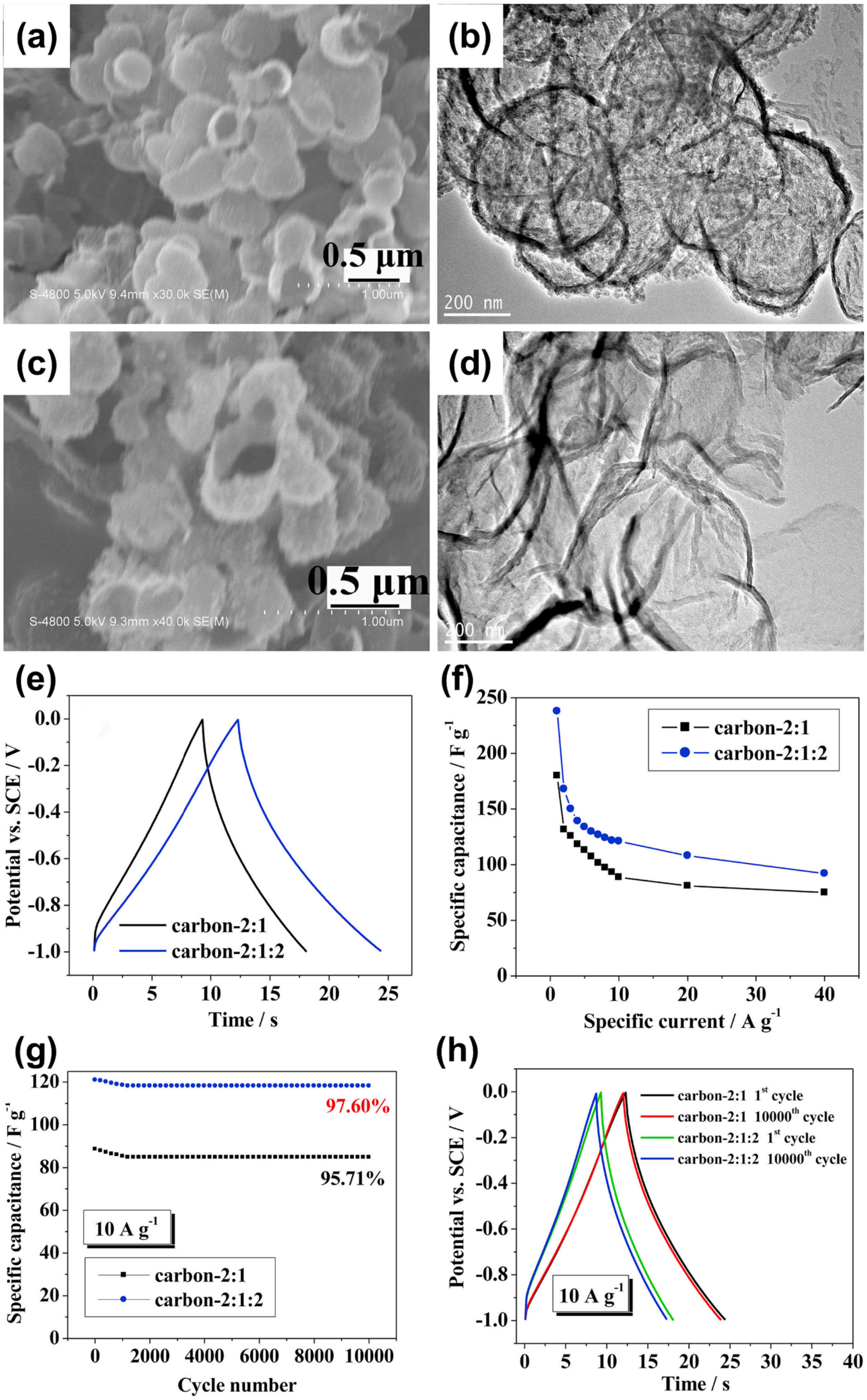

Fig. 4. (a) and (b) are, respectively, FESEM and HRTEM images of Carbon- 2:1 where 2:1 is the PTFE: $CaCO_3$ mass ratio (without N); (c) and (d) are, respectively, FESEM and HRTEM images of Carbon-2:1:2 (doped with N); (e) Galvanostatic charge–discharge curves; (f) specific capacitances as a function of specific current; (g) and (h) show cycling stability and Galvanostatic charge–discharge curves of the 1st and 10,000th cycles. Adapted with permission from Jiang et al. (2014). Copyright 2014, Elsevier.

sacrificial material. After thermal treatment, PS foam was blended with polyacrylamide (PAN) to generate CNFs with micro-mesoporous multichannels and a large surface area. The material was successfully applied with excellent capacitance retention, high cycle stability, and electrical conductivity Ishita and Singhal, (2020).

4.2.1.2. Two-dimensional (2D) carbon nanomaterials. In two-dimensional (2D) materials, two of the dimensions are outside the nanoscale. This material shows a layered structure with strong in-plane bonds and weak van der Waals interaction between layers. The central material representing this spatial structure is graphene. Nevertheless, there are other layered materials. Hybridized sp^2 carbon atoms, assembled like a honeycomb lattice, are responsible for the exceptional characteristics of graphene (e.g., excellent surface area and remarkable electronic, thermal, and mechanical characteristics) Novoselov et al. (2012). Therefore, graphene and its analogs have been broadly and deeply studied in previous years, mainly in the energy storage field Novoselov et al. (2012). Furthermore, as previously mentioned, 2D nanomaterials can expand interlayer spacing for ion storage, improving electron transmission and electrochemical conductivity (Zheng et al., 2020).

Polymer waste has recently become a sustainable carbon source for the large-scale production of layered carbon nanomaterials using pyrolysis. For example, Pandey et al. (2019) converted around 35 kg of the plastic waste mix based on PP, PE, and PS into 5.25 kg of pure graphene nanosheets using slow pyrolysis in a single bath. The intrinsic capacitance of these materials, evaluated by the electronic density of states (DOS) profiles, pointed to excellent performance. In another study, a mixture (20 kg) of plastic waste (PP, PE, and PET) was pyrolyzed with bentonite clay to produce graphene nanosheets (GNs). The supercapacitor containing GNs as its active electrode material layer showed impressive specific capacitance (398F/g at 0.005 V s^{-1}) Pandey et al. (2021).

Catalytic pyrolysis is another way of efficiently producing carbon nanosheets with a porous 2D nanostructure once combined with chemical activation. KOH is a pore-forming agent that generates pore networks in carbon structures, improving their electrochemical characteristics. Accordingly, Liu et al. (2021) used catalytic pyrolysis of PP waste to produce carbon nanosheet-based supercapacitor electrodes. In this process, ferrocene and sulphur were applied as catalytic agents during pyrolysis. The new product obtained after KOH activation (ACNS-4) had a rough surface, indicating mesopores and micropores on its surface (Fig. 5**a and b**).

As shown in Fig. 5**c**, the porosity induced by KOH creates a material with a huge specific surface area of 3200 m^2/g and a mix of micro-, meso-, and macropores, where the *meso*-macropore volume is as high as 2.48 cm^3 g^{-1} (Fig. 5**d**). The presence of different pore sizes can improve ion diffusion and the performance of the electrode. Thus, as the electrode, the carbon nanosheet showed a dominant double-layer (Fig. 5**e**) and capacitive behaviour (Fig. 5**f**), with the highest specific capacitance of 349F/g at 0.5 A/g and the highest stability compared to the other analysed samples, as shown in Fig. 5**g and h**. The high capacitance levels obtained in each case resulted from several effects, such as the enormous specific surface area, the horizontal mobility of electrolyte ions upon the superficial carbon, and the presence of *meso*-macropores in carbon nanosheets, and oxygen-containing functional groups Liu et al. (2021). The authors created a symmetric supercapacitor to demonstrate its performance in practical applications. They carried out cyclic voltammetry and galvanostatic charge–discharge analysis to find the specific capacitance of the system. As a result, the new device showed specific capacitance of 204 F/g at 0.5 A/g, high energy density (23 Wh kg^{-1}) with power density of 225 W kg^{-1}, and great capacitance retention (92%) after 10,000 cycles (Fig. 5**i–k**). These values were enough to light a red LED bulb for over 80 s, which means that this new device based on carbon nanosheets is a potential alternative for energy storage.

Interestingly, Wen et al. (2019) transformed a mix of plastic waste obtained from diverse sources (PP from waste woven bags, PE from waste vessels, PS from waste foam sheets, PET from waste beverage bottles, and PVC from waste sewage pipes) into carbon nanosheets. All the plastic was mixed with organo-montmorillonite (OMMT) and pyrolyzed at 700 °C for 10 min, followed by KOH activation. OMMT can act simultaneously as both a template and catalyst in this approach, promoting the decomposition of plastic waste and the growth of nanosheets. Electrodes built from these porous carbon nanosheets showed specific capacitance of 207F/g in the electrolyte 6 M KOH. The intense efforts to magnify the carbon nanosheet properties have led researchers to use pseudocapacitive materials, such as manganese dioxide (MnO_2) merged with carbon nanomaterials. This type of nanocomposite has

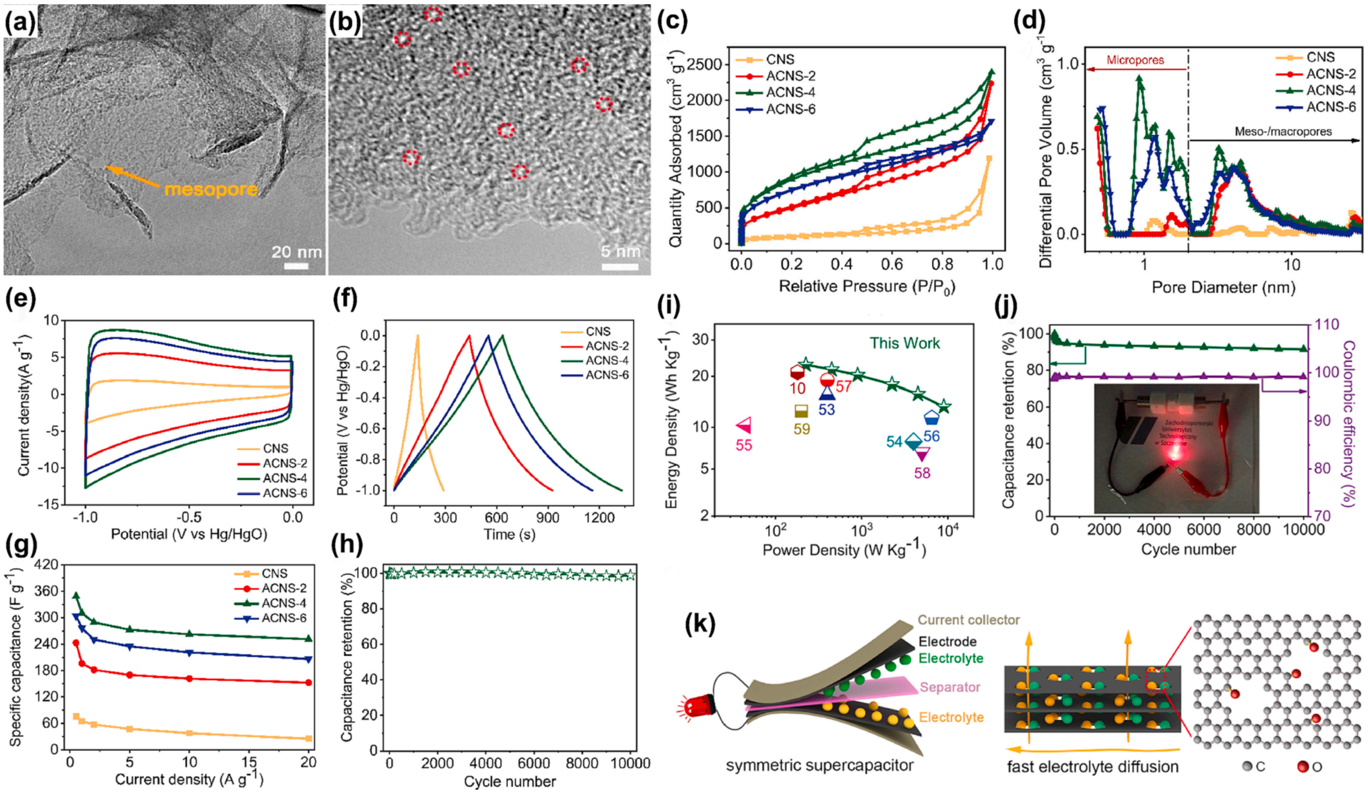

Fig. 5. (a) ACNS-4 TEM and (b) HRTEM images; (c) N_2 adsorption–desorption isotherms and (d) pore size distributions of samples. Electrochemical performance of samples in a three-electrode system using 6 M and KOH electrolyte: (e) CV curves at 20 mV s^{-1}, (f) GCD profiles at 0.5 A/g, (g) specific capacitance versus current densities, (h) cycling performance at 5 A g^{-1}; electrochemical performance of ACNS-4 in a two-electrode system using 1 M Li_2SO_4 electrolyte: (i) energy density versus power density; (j) cycling performance and coulombic efficiency at 10 A/g; and (k) schematic drawing of the fabricated supercapacitor. Adapted with permission from Liu et al. (2021). Copyright 2021, Elsevier.

shown impressive electrochemical performance because MnO_2 can provide significant specific capacitance and energy density. As opposed to carbon materials, it offers excellent stability and high-power density. Min et al. (2019) showed the positive synergistic interaction between porous carbon nanoflakes and MnO_2. The composite was produced through pyrolysis of PS waste followed by MnO_2 nanosheet deposition on the surface of carbon nanomaterial. The resulting hybrid material showed capacitance of 247F/g at 1 A/g in lithium chloride (LiCl) electrolyte. It has excellent stability and capacitance retention.

Chang et al. (2018) also focused on producing porous carbon nanosheets from different PVC plastic wastes. The authors used KOH as a dehalogenation agent, dimethylformamide as both the N source and solvent, and dimethyl sulfoxide as the S source. The N- and S-doped carbonaceous materials were obtained via KOH-assisted room-temperature dehalogenation and pyrolysis. The final materials presented a significant number of micropores after activation. Charge-discharge performance was tested in different electrolytes, and the materials maintained specific capacitance of ~ 399F/g at 1.0 A/g in 6 M KOH.

4.2.1.3. Three-dimensional (3D) carbon nanomaterials. Based on the strict definition, 3D nanostructures are materials in which no dimension is limited by the nanoscale Kumar et al. (2021). 3D nanostructures are mainly represented by mesoporous carbon. Among 0D to 3D dimensions, the 3D has been, undoubtedly, the most considerably widespread, besides materials with these properties being of great interest to the eyes of the scientific community as supercapacitor electrodes. When used as electrodes, the interconnected structures in 3D materials are responsible for fast ionic transport and mechanical constancy. Furthermore, 3D nanostructures can surpass the weaknesses of lower-dimension materials (0D, 1D, and 2D), such as irreversible aggregation.

For instance, Kumar et al. (2018) converted poly(styrene-co-acrylonitrile) (SAN), a type of plastic waste usually applied in the outer casting of electronic devices, into porous carbon by pyrolysis and physical activation. The authors used different pyrolysis temperatures (700, 800, and 900 °C) and after that, the pyrolyzed material was physically activated under CO_2 atmosphere. The carbonized material pyrolyzed at 900 °C and physically activated had the highest specific surface area (1357.82 m^2/g) and pore volume (0.2 $cm^3\ g^{-1}$) among its counterparts. The CO_2 (used as an oxidant agent) promotes pore opening by eliminating the species active in the pores of feedstock, reflecting an increase in pore volume. Although there is some disagreement on the direct relationship between surface area and capacitance, the materials with the largest surface area had the best capacitive performance (217F/g).

By relying on the chemical vapor deposition (CVD) method, Liang et al. (2019) designed an innovative approach based on pyrolysis-deposition to recycle PS waste and to convert it into valued mesoporous carbon. Mesoporous silica (SBA-15) was applied as the rigid template, and ferric nitrate ($Fe(NO_3)_3$) as the catalyst. The methodology produced a highly mesoporous carbon electrode with multi-channels to increase ion intercalation. The authors observed that the manufacture of mesoporous carbon depends on the pyrolysis temperature. The PS product cannot be placed in the mesoporous SBA-15 at low pyrolysis temperatures. In contrast, higher pyrolysis temperatures lead to the collapse of the pores in the mesoporous carbon. Nevertheless, the well-organized mesoporous carbon showed impressive electrochemical action.

Ma et al. (2020) also designed a 3D-ordered permeable carbon from the catalytic pyrolysis of PS, followed by KOH activation. Iron (III) oxide (Fe_2O_3) particles promoted polymer decomposition and the construction of a 3D macroporous structure. Consequently, the leaky carbon presented an extreme specific capacitance of 284.1 $F\ g^{-1}$ at 0.5 A/g. Through pyrolysis, a wide range of carbon sources derived from polymer waste have been transformed into mesoporous carbon materials. Some examples are compact discs (CDs) Farzana et al. (2018), PS foam Deka et al. (2020), and polyurethane (PU) Schneidermann et al. (2019). Almost all related studies used some activation method. Highly porous structures offer abundant and accessible electrochemical active sites to accommodate numerous charges and provide a fast charge/discharge route and a backbone for active materials V. H. Fragal et al. (2020).

As mentioned before, the combination of EDLCs and faradaic reaction leads to an impressive increase in energy and power density in the electrode, allowing to produce smart devices for energy accommodation. For example, Meng et al. (2020) synthesized a 3D hierarchical porous carbon composed of nickel cobaltite ($NiCo_2O_4$), graphene, and waste PU foam (PGNC). The authors combined thermal and pyrolysis processes. PU foam carbonization provides a 3D interconnected pore structure for ion intercalation/deintercalation. The hierarchical structure showed high specific capacity and long stability (1900F g^{-1} at 1 A/g in 6 M KOH).

Another nanocomposite formed by $NiCo_2O_4$ was reported by Alhokbany et al. (2020). The authors used pyrolysis to convert PET waste into a carbon source and produce a new $NiCo_2O_4$@nitrogen-doped carbon (NC) nanocomposite. The superior conductivity, exceptional redox activity of NiCo2O4, and the remarkable stability of permeable carbon provide special electrochemical implementation, showing specific capacitance of 913F/g at 1 A/g in 6 M KOH.

Aiming to improve the capacitance of activated carbon, Sangeetha et al. (2020) used molybdenum disulphide (MoS_2) to design a new electrode. First, the authors prepared activated carbon via pyrolysis of plastic bottles (PET), followed by KOH activation (PAC). After that, the MoS_2-C nanoflowers were synthesized via a hydrothermal method using water and ethylene glycol. Electrochemical performance can be improved by the heterojunction of PAC and MoS_2-C (Fig. 6**a**). The PAC derived from PET had high specific surface area of 899 m^2/g, with a remarkable microporous structure, as shown in Fig. 6**b** (FESEM image) and **6c** (TEM image). Meanwhile, the MoS_2-C showed a flower structure formed by randomly oriented sheets, as shown in Fig. 6**d** (FESEM image) and **6e** (TEM image). The arrangement of the layers contributes to improving the system's performance due to the ease of ion diffusion in the electrodes. Thus, a new material from PAC and MoS_2-C was designed to produce a symmetric electrochemical supercapacitor (SEC) and a hybrid electrochemical supercapacitor (HEC). To produce SEC, the authors used a cathode to anode ratio of 2: 1 (PAC/MoS_2-C), where PAC was the cathode and 2: 1-PAC/MoS_2-C was the anode for HEC. The material showed capacitive behaviour in both systems (Fig. 6**f-i**), created by Na^+ ion adsorption and desorption on the electrode surface. In addition, the C atoms in the MoS_2 structure contribute to the EDLC behaviour. As a result, the new electrode could deliver a specific capacitance of 183 and 241F/g for SEC and HEC, respectively (Fig. 6**g-j**), and good capacitance retention (Fig. 6**h-k**).

Another interesting study showed the recycling of poly(lactic acid) (PLA) from industrial waste, presenting a change of view on plastic waste recycling for supercapacitor platforms. PLA used as filament can reach capacitance values 75 times higher than those of commercially available conductive PLA filaments being £0.15 the cost per electrode Wuamprakhon et al. (2022). The process is based on blending PLA, carbon black, and poly(ethylene glycol) in a chamber (170 °C), showing a new direction for plastic waste recycling based on a simple, environmentally economical treatment method combined with low energy consumption Wuamprakhon et al. (2022).

Several other inorganic materials have been combined with porous carbon originating from plastic waste to produce smart devices for supercapacitors. Pyrolysis and chemical activation methods are used to produce composites constituted by molybdenum carbides (MoC/Mo_2C) Mir and Pandey, (2019), magnetite (Fe_3O_4) Kaipannan et al. (2019), and manganese dioxide (MnO_2) Mu et al. (2020). Overall, these smart devices offer different ways of recycling plastic waste and converting it into 3D hierarchical mesoporous carbon. Their excellent specific surface area and porous structure are platforms for other materials. These features allow fast ion intercalation/deintercalation and mechanical

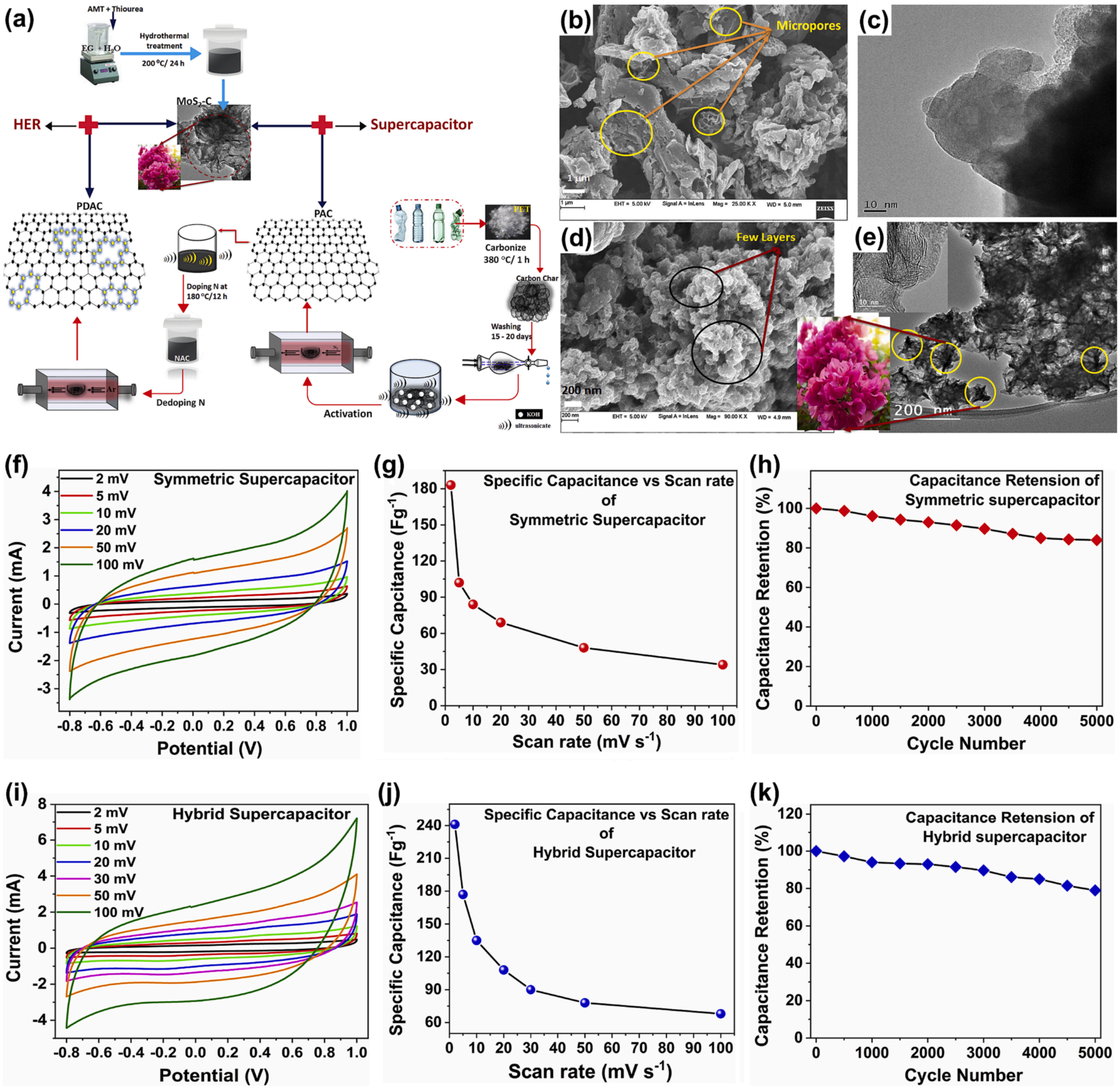

Fig. 6. (a) Experimental procedure to obtain PAC/MoS_2-C. (b) and (c) FESEM and TEM images of PAC; (d) and (e) FESEM and TEM images of MoS_2-C. Electrochemical evaluation of PAC/MoS_2-C: (f) CV curve for symmetric supercapacitor; (g) specific capacitance; (h) cycling performance. Hybrid supercapacitor: (i) CV; (j) specific capacitance; and (k) cycling performance. Adapted with permission from Sangeetha et al.(2020). Copyright 2020, Elsevier.

stability, which makes mesoporous carbon attractive for producing supercapacitors (see Table 1).

5. End-use of supercapacitors. Recycling or reuse?

With the highly increased use of supercapacitors, end-of-life disposal of manufacturing scraps and components has become an important issue. Waste supercapacitors are classified as hazardous material, and it is necessary for specific treatment according to EU Directive 2002/96/EC on Waste Electrical and Electronic Equipment Jiang and Pickering, (2016). So far, researchers have been focusing on viable and sustainable recycling technology from the point of view of the legislation on recycling. However, the rules for recycling electrochemical devices, such as capacitors and batteries, are already consolidated in numerous countries. The primary purpose is to recuperate precious metals in the electrodes Bernardes et al. (2004). Supercapacitors do not contain precious metals. However, huge quantities of electrolytic solutions are dispersed in activated carbon. Thus, the aim is to recycle the electrolytic solution instead of carrying out the combustion procedure. Even though activated carbon is relatively cheap, reusing it would partially offset the costs related to the recycling process.

Several hazards may be faced in the supercapacitor recycling process, including the solvents used to dissolve electrolytes, and the electrolytes themselves Béguin et al. (2014). The primary method for recycling organic solvent is through evaporation after the total disintegration of supercapacitor waste. The next stage is to isolate the activated carbon from the organic salt and polymer binders. The final process is cost-effective and beneficial for the environment as dangerous elements are removed after the supercapacitor device has completely degraded.

A simple, easy, low-cost, and environmental friendly method for recycling supercapacitors was proposed by Vermisoglou et al. (2016). They recovered fundamental components such as tetraethyl ammonium tetrafluoroborate ($TEABF_4$) electrolytes (leading to a recovery of ∼ 70%), carbonaceous material, aluminum foil as a collector, and paper as

Table 1
Condenses the different carbon structures derived from plastic waste, describing their basic materials, waste source, synthesis method, and capacitive performance.

Category	Selected examples	Polymer Waste Source	Synthesis method	Carbon production temperature and reactor configuration	Electrochemical properties	Ref
0D	Spherical Nanoporous Carbon	PTFE	Pyrolysis	700 °C / Horizontal tube furnace	237.8 F.g^{-1} at 1 A.g^{-1}	Jiang et al. (2014)
1D	Multiwalled Carbon Nanotubes	Mix of PET, PE, PA, and PP	pyrolysis, catalytic cracking, CCVD	550 °C / Horizontal tube furnace	34.1F.g^{-1} at 0.5 A.g^{-1}	Abbas et al. (2021)
	Carbon Nanofibers	PS foam	Electrospinning / Pyrolysis	800 °C / Horizontal tube furnace	271.6F.g^{-1} at 0.5 A.g^{-1}	Ishita and Singhal, (2020)
2D	Graphene nanosheets	Mix of PP, PE and PET	Pyrolysis	Two steps 450 °C and 945 °C / Horizontal tube furnace	398F.g^{-1} at 5 mV.s^{-1}	Pandey et al. (2021)
	Carbon nanosheets	PP from centrifuge tubes	Catalytic Pyrolysis	700 °C / Vertical furnace	349F.g^{-1} at 0.5 A.g^{-1}	Liu et al. (2021)
	Carbon nanosheets	Mix of PP, PE, PS, PET and PVC	Catalytic Pyrolysis	700 °C / Horizontal tube furnace	207F.g^{-1} at 0.2 A.g^{-1}	Wen et al. (2019)
	Carbon nanosheets	PET from plastic bottles	Catalytic Pyrolysis	700 °C / Horizontal tube furnace	183F.g^{-1} at 0.1 A.g^{-1}	Wen et al. (2020)
	Graphene nanosheets	Mix of PP, PE, and PS	Catalytic Pyrolysis	Two steps 400 °C and 900 °C / Horizontal tube furnace	19.52F.g^{-1} at 5 mV.s^{-1}	Karakoti et al. (2021)
	Carbon nanoflakes/MnO_2 composite	PS foam from packages	Pyrolysis	973 K / Vertical furnace	247F.g^{-1} at 1 A.g^{-1}	Min et al. (2019)
	Carbon nanosheets	PVC plastics products	Pyrolysis	600 °C / Horizontal tube furnace	399F.g^{-1} at 1.0 A.g^{-1}	Chang et al. (2018)
3D	Nanoporous carbon	SAN plastics from printers	Pyrolysis/ Chemical activation	900 °C / Horizontal tube furnace	217F.g^{-1} at 5 mV.s^{-1}	Kumar et al. (2018)
	Nitrogen-doped porous carbons	PS foam from packages	Pyrolysis/ Chemical activation	700 °C / Horizontal tube furnace	327F.g^{-1} at 1.0 A.g^{-1}	Deka et al. (2020)
	(3D) hierarchically porous carbon	PS from plastic packaging	Catalytic Pyrolysis/ Chemical activation	700 °C / Horizontal tube furnace	284.1F.g^{-1} at 0.5 A.g^{-1}	Ma et al. (2020)
	(3D) network structure porous carbon	PS foam from packages	Pyrolysis	600 °C / Horizontal tube furnace	208F.g^{-1} at 1 A.g^{-1}	Zhang et al. (2018)
	Nanoporous carbon/ $NiCo_2O_4$ composite	PU foam	Solvothermal / Pyrolysis	900 °C / Horizontal tube furnace	1900F.g^{-1} at 1 A.g^{-1}	Meng et al. (2020)
	$NiCo_2O_4$/nitrogen carbon nanocomposite	PET plastics	Pyrolysis	450 °C / Horizontal tube furnace	913F.g^{-1} at 1 A.g^{-1}	Alhokbany et al. (2020)
	MoS_2/Activated carbon composite	PET from plastic bottles	Pyrolysis/ Chemical activation	800 °C / Horizontal tube furnace	288F.g^{-1} at 2 mV.s^{-1}	Sangeetha et al. (2020)
	Carbon/Fe_3O_4 nanocomposite	Toner discarded	Pyrolysis	300 °C / Vertical furnace	536F.g^{-1} at 3 A.g^{-1}	(Kaipannan et al. (2019))
	Porous carbon nanosheet/ MnO_2 composite	PET from plastic bottles	Catalytic Pyrolysis	700 °C / Vertical furnace	210.5F.g^{-1} at 0.5 A.g^{-1}	Mu et al. (2020)

PTFE = Polytetrafluoroethylene; **PA** = polyamide; **PS** = Polystyrene; **PE** = Polyethylene; **PET** = Poly(ethylene terephthalate); **PU** = Polyurethane; **PP** = Polypropylene; **PC** = Polycarbonate; **SAN** = Poly(Styrene-co-acrylonitrile); **PVC** = Poly(vinyl chloride); **CCVD** = Catalytic Chemical Vapor Deposition.

a separator. The method includes the mechanical crushing of the supercapacitor and the separation of paper and aluminum foil by sifting them from the carbonaceous material and electrolytes (Table 2). The extraction of electrolytes was based on solubility in water and separation by filtering and distillation. The recycled carbonaceous material exhibited supercapacitor behaviour, enabling reuse.

Jiang and Pickering, (2016) described the recycling of carbonaceous material based on shredding and mild thermal treatment after using an end-of-life supercapacitor. The first step consisted of shredding using a Retsch cutting mill and thermal treatment at 200 °C. The as-obtained fine particles had a Brunauer–Emmett–Teller (BET) surface area of 1200 m^2/g. Another interesting application is using recycled carbon material from commercial supercapacitors as a low-cost adsorbent for the high-efficiency removal of heavy metals in aqueous solutions Wu et al. (2020).

Carbon materials can also be recovered from end-of-life supercapacitors using simple thermal activation, turning them into stable and high-voltage supercapacitors. Fig. 7 illustrates the recycling process of carbon materials from spent supercapacitors and their back-integration into high-voltage and super-stable supercapacitors Chodankar et al. (2022). The authors have recovered carbon which retains its excellent structural properties, like a large specific surface area (∼1716 m^2/g) and

Table 2
Components and method of recycling of supercapacitors.

Component Eletrolyte	Carbon	Method of recycling	Ref.
Tetraethyl ammonium tetrafluoroborate (TEABF$_4$)	Activated charcoal Carbon nanotubes	Mechanical shredding Filtring, distillation	Vermisoglou et al. (2016)
//	Activated carbon	Discharging pre-treatment, ultrasound, drying	Wu et al. (2020)
Acetonitrile	Activated carbon	Shredding and mild thermal treatment	Jiang and Pickering, (2016)
/	Activated carbon	Thermal activation	Chodankar et al. (2022)
//	Activated carbon	Scrapping, chemical activation (KOH)	Zhang et al. (2022)

a high degree of graphitization with well-oriented graphitic layers. The renovated supercapacitor shows cycling stability for over 300,000 cycles, with 99% capacitance retention. This high performance of recovered materials from waste capacitors may encourage future research associated with waste recovery, assisting in sustainable practices and economy.

6. Final considerations and perspectives for plastic waste

Plastic waste represents 12% of the world's solid waste Kaza et al. (2018). Industrial manufacture of plastics may generate 12 billion metric tons of plastic waste by 2050. However, plastic waste is a carbon-rich resource, making it useful as feedstock for carbon nanostructure production.

This review provides an overview of the sustainable management of plastic waste. It demonstrates how trash, such as plastic, can be transformed into carbonaceous materials using the pyrolysis method. Also, different methodologies, including CVD, electrospinning, hydrothermal, and solvothermal techniques to produce carbon-based materials of 0, 1, 2, or 3 dimensions for supercapacitors are presented. Highly efficient

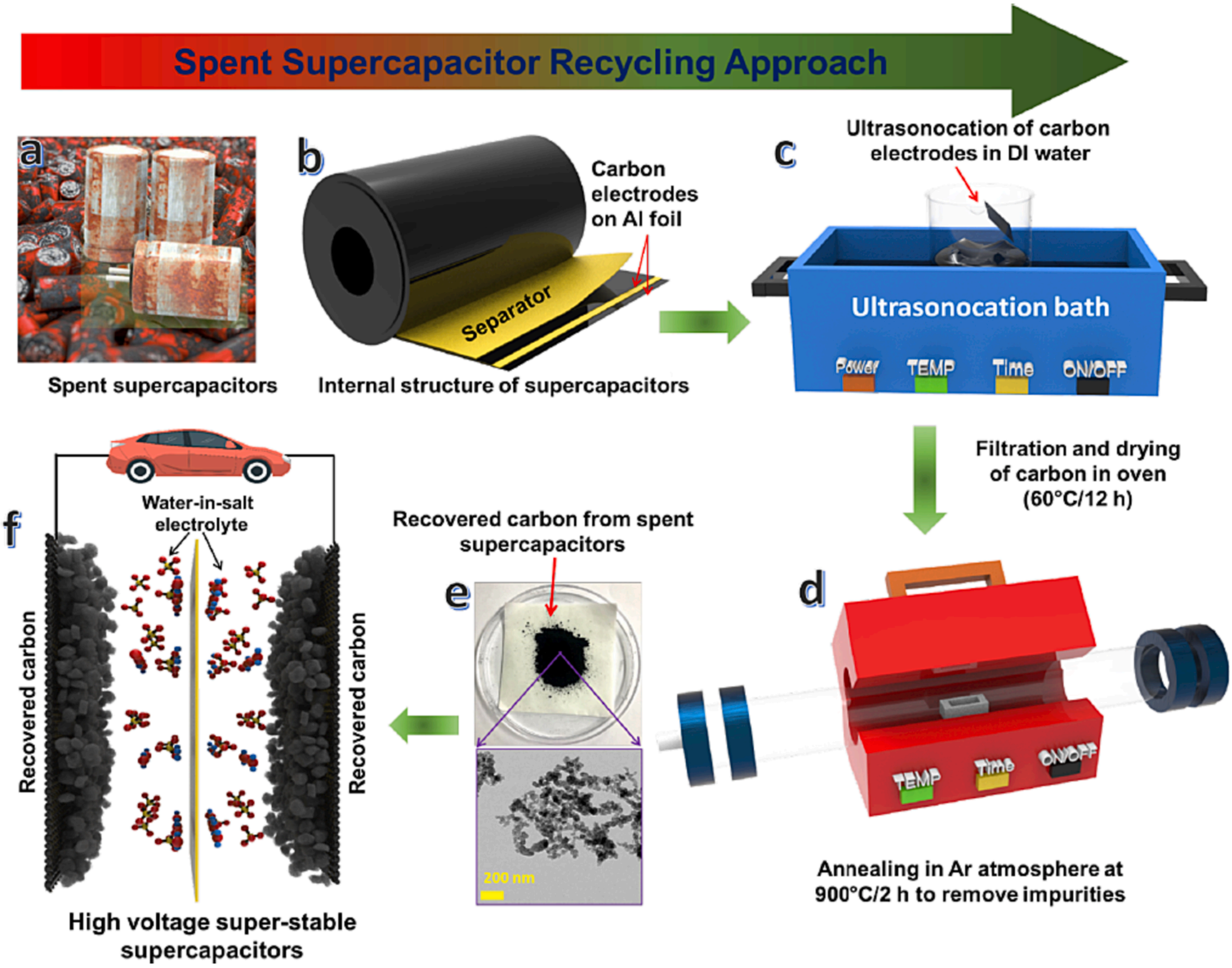

Fig. 7. Schematic illustration of recycling of carbon materials from the spent supercapacitors and their back-integration into high-voltage and super-stable supercapacitors: (a) schematic of the collected spent supercapacitors, (b) internal structure of the supercapacitor, in which two carbon-coated aluminum foil electrodes are separated by the separator, (c) carbon-coated aluminum foils are sonicated in de-ionized (DI) water for 2 h and further filtered and dried in an oven to collect the carbon from aluminum foil, (d) inert atmosphere (Ar) annealing for 2 h at 900 °C with ramping temperature of 5 °C/min to remove the impurities from the spent supercapacitor carbon, (e) the optical and TEM image for the recovered carbon from the spent supercapacitor, and (f) the schematic of re-assembled supercapacitor with the recovered carbon electrodes and 17 M NaClO$_4$ water-in-salt electrolyte. Reproduced with permission from Chodankar et al (2022). Copyright 2022, Elsevier.

nanomaterials have been produced to save energy. This strategy helps to minimize the immeasurable plastic waste problem and, simultaneously, to drop the prices of supercapacitors. The rise of efficiency and the reduction of costs in producing energy storage devices are requirements for fast development in numerous fields.

More importantly, the article lists some interesting papers that offer a new sustainability cycle that could be opened by recycling and reusing supercapacitors' components. Recycling material from already-used energy storage devices is a new trend, and the good performance brings integrated perspectives on using, recycling, and reusing towards the evolution of sustainability.

Based on recent advances, transforming plastic waste into carbon nanomaterials is an excellent alternative to energy storage. Nevertheless, it should be acknowledged that, despite the significant technical progress in this field, some drawbacks still need to be improved, including sustainable strategies. So, future research needs to focus on the following points.

1. As mentioned in this review, currently, of the different techniques for the management of plastic waste, pyrolysis stands out. This technique offers social, economic, and environmental advantages compared to incineration. However, it has some environmental and technical challenges, including the cost and complexity of the processing. Not all discarded plastic can be recycled using pyrolysis; most of it is wrongly disposed of or incinerated, contributing to environmental pollution. Therefore, this oversized issue requires companies, universities, and governments to make joint efforts to address their energies to improve the existing technologies or to develop new processes to save energy and improve waste management, if possible.
2. From the standpoint of electrodes, the cost of producing supercapacitors is relatively high, which limits technological advancements. Future works should focus on methodologies for producing a wide variety of advanced materials to reduce the cost and increase the efficiency of electrodes. Although carbon has been demonstrated to have high potential as electrode material, the advance of technology requires more and more effective devices. In this sense, hybrid supercapacitors have proved to be an excellent alternative.
3. From the economical point of view, methodologies that produce nanostructures, like electrospinning, CVD, hydrothermal, and solvothermal methods, also have limitations related to each technique. Cost, scale-up, and difficulty in reaching all requirements for nanomaterials are other concerns faced.

Thus, we believe in a promising future, perfectly possible from both scientific and technological perspectives.

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.

Data availability

No data was used for the research described in the article.

Acknowledgments

The authors acknowledge Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (Grant #150866/2020-8**,** 165734/2020-5, 408767/2021-9**,** 307429/2018-0 and 409258/2022-9) for financial support and the concession of a scholarship. Special thanks to Serrapilheira Institute (grant number Serra-**2018- 4357**) for technical support.

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