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Review

Green Nanocomposites for Energy Storage

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Abstract: The green nanocomposites have elite features of sustainable polymers and eco-friendly nanofillers. The green or eco-friendly nanomaterials are low cost, lightweight, eco-friendly, and highly competent for the range of energy applications. This article initially expresses the notions of eco-polymers, eco-nanofillers, and green nanocomposites. Afterward, the energy-related applications of the green nanocomposites have been specified. The green nanocomposites have been used in various energy devices such as solar cells, batteries, light-emitting diodes, etc. The main focus of this artifact is the energy storage application of green nanocomposites. The capacitors have been recognized as corporate devices for energy storage, particularly electrical energy. In this regard, high-performance supercapacitors have been proposed based on sustainable nanocomposites. Consequently, this article presents various approaches providing key knowledge for the design and development of multi-functional energy storage materials. In addition, the future prospects of the green nanocomposites towards energy storage have been discussed.

Keywords: eco-friendly; nanomaterial; nanofiller; energy; supercapacitor

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1. Introduction

Green or eco-friendly or eco-polymers are named due to their environmentally friendly nature and production from some renewable resources [1,2]. These polymers are usually biodegradable or compostable [3–5]. Initial research has focused on the use of green polymers [6–8]. Later research has turned towards the formation of green nanocomposites using eco-polymers [9,10].

Green or eco-friendly nanomaterials have several advantages of sustainablility, low cost, eco-friendliness, and high performance [11–13]. Different natural and synthetic green polymers and nanofillers have been used to develop green nanomaterials [14]. In the green polymeric nanocomposites, the features of both the green polymers and eco-nanofillers have been incorporated in the high-performance materials [15]. Use of the natural and synthetic green or eco-polymers or eco-friendly polymers and related materials have extended their use in various industrial fields [16–18]. Eco-friendly nanofillers used with the eco-polymers are also environmentally friendly. The eco-nanofillers include the use of metal nanoparticles, polymer nanoparticles, nanoclays, inorganic nanoparticles, carbon nanoparticles, and a similar range of other nanoparticles. The derived nanocomposites from eco-friendly polymers and eco-nanofillers are currently known as green polymeric nanocomposites. The synergistic effects of the eco-friendly polymers and green nanofillers have resulted in several enhanced physical properties, eco-friendliness, and biodegradability of the resulting green nanocomposites [19,20]. The properties of the green nanocomposites usually rely on the nanofiller content, processing technique, and matrix-filler interactions. The green nanocomposites have found varying solicitations in energy devices, electronics, aerospace, packaging, environmental, and biomedical applications. The energy storage devices are the most demanding expedients in the energy sector due to the environmental glitches [21,22]. These devices provide a solution to the use of unverifiable energy sources such as petroleum or coal. In other words, green nanocomposites are alternatives to the pollution-causing energy sources. The most common type of energy storage devices are capacitors [23]. Among various types of capacitors, supercapacitors are the most efficient ones. Supercapacitors have been researched for their lightweight, durability, and enrichment of energy storage, energy density, and specific capacitance characteristics. The green nanocomposites have expanded research inquisitiveness due to their inexpensiveness, light weight, sustainability, biodegradability, and recyclability properties [24,25]. The eco-friendly nanocomposites have been utilized in numerous engineering applications in the energy sector especially energy storage devices [26–28]. Green polymeric nanocomposite reveals high-performance energy storage, however, their use in advanced energy applications is still challenging [29,30].

In this review, the use of green nanofillers and green polymers in green nanocomposites has been enlightened. This review has been developed focusing on the energy storage applications of sustainable nanocomposites. This article also presents the future prospects of the multi-functional next-generation green nanocomposites. Since revealing the importance of green polymeric nanocomposite, this review has focused on sustainable polymers, nanofillers, and the resulting nanocomposites. To the best of our knowledge, this review paper is novel in the literature due to the originality of the outline and the included literature compared with the previous literature reviews [31,32]. This review is all-inclusive and aims to include the essential technical and commercial developments of green nanocomposites in the energy sector.

2. Green or Eco-Friendly Nanocomposites

Among renowned eco or green polymers is a range of synthetic and natural polymers such as poly(vinyl alcohol), poly(ethylene glycol), poly(ethylene oxide), poly(lactic acid), polyamide, polycarbonate, polyurethane, cellulose, starch, etc. (Table 1) [33].

Table 1. Some green synthetic and natural polymers.

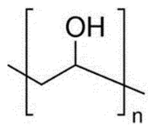
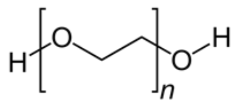
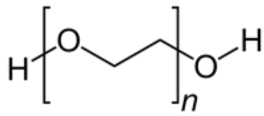
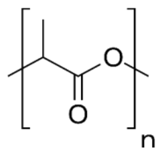
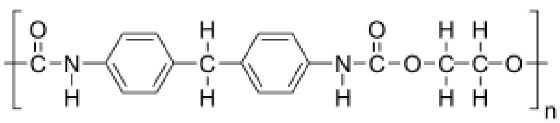
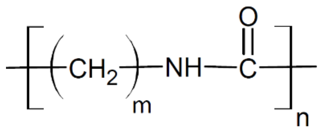
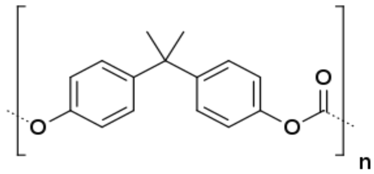
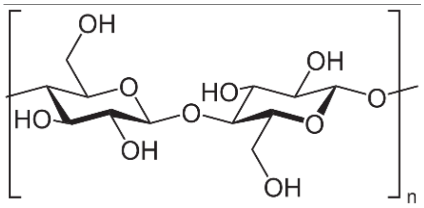
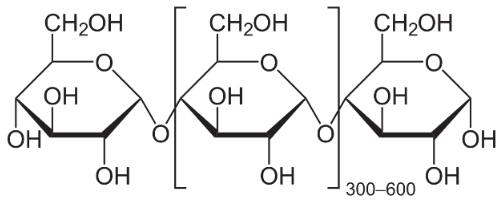
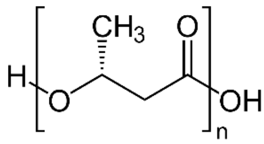
Green Polymer	Structure
Poly(vinyl alcohol)	
Poly(ethylene glycol)	
Poly(ethylene oxide)	
Poly(lactic acid)	
Polyurethane	

Table 1. *Cont.*

Green Polymer	Structure
Polyamide	
Polycarbonate	
Cellulose	
Starch	
Polyhydroxyalkanoate	

The green polymers have been prepared through several green synthesis methodologies [34,35]. The green polymers have found applications in adhesives [36], membranes [2], coatings [37], drug delivery [38], and other biomedical applications [39,40]. Green nanofillers used with the polymers are mostly biodegradable in nature. Figure 1 shows a few green nanofillers. Chitosan has been used as a successful green nanofiller [41,42]. Lignin has also played an important role as a green nanofiller [43,44]. Lignin has been used as a nanofiller in several synthetic and natural polymer matrices such as polystyrene, polyethylene, poly(ethylene oxide), poly(vinyl chloride), polyester, and poly(lactic acid), etc. [45,46]. Phyllosilicate nanoclays such as montmorillonite have gained considerable research attention [47,48]. Montmorillonite is a well-known ecological nanofiller [49–51]. Nanoclays have been used with biodegradable polymers to form green systems [52,53]. Among carbon nanofillers, graphene, graphene oxide, and carbon nanotube nanofillers have been widely used with green polymers [54–56]. These nanofillers have enhanced the heat stability, mechanical features, charge transport, thermal conductivity, flame retardancy, antimicrobial features, and biodegradability of the green nanocomposites.

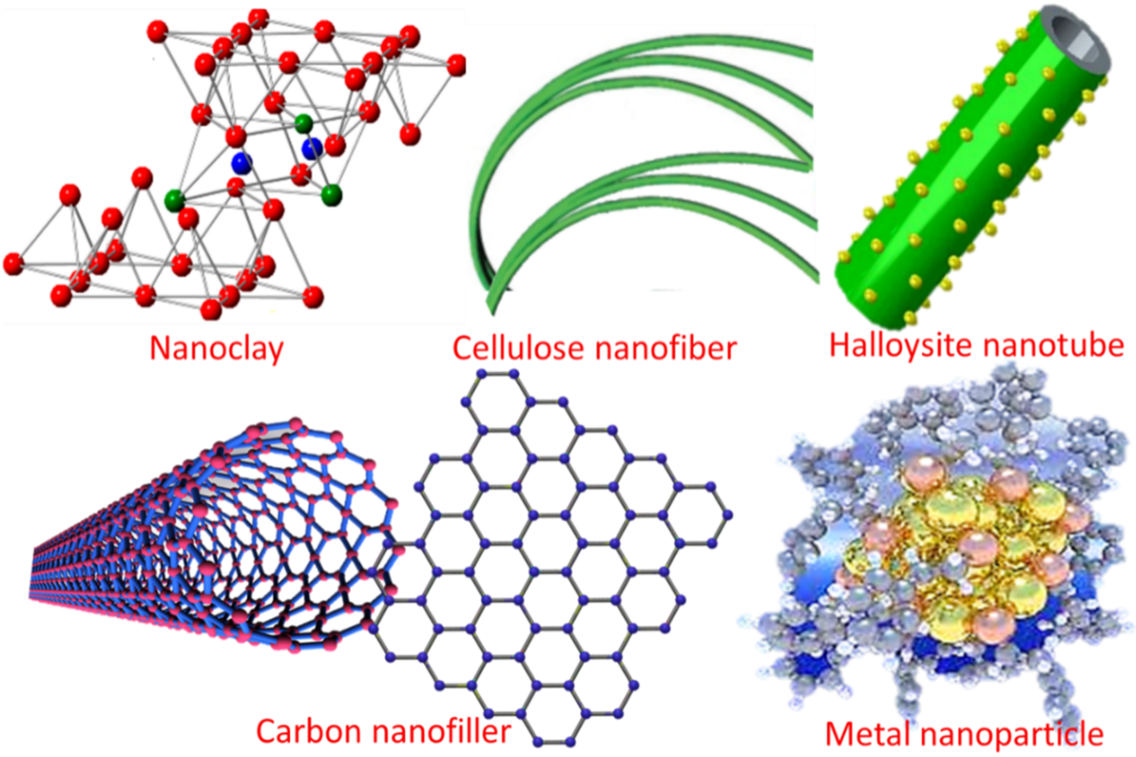


Figure 1. Green nanofillers.

Polyethylene glycol (PEG) is a water-soluble non-hazardous polymer [57–59]. It is also considered a green polymer. The PEG has been reinforced with nanofillers to form nanocomposites [60]. The glass transition temperature of PEG has been found to alter with the addition of additives and nanofillers [61]. In addition, additives and nanofillers have been used to enhance the mechanical properties of the PEG-based nanocomposites [62]. Cavallaro et al. [63] prepared green nanocomposite based on PEG and halloysite nanotubes. The dispersion properties of halloysite nanotubes in the PEG matrix have been studied. The halloysite nanotubes were found to enhance the mechanical properties of the PEG matrix. Due to barrier properties provided by the halloysite nanotubes, the green nanocomposite was used for packaging purposes. Gopi et al. [64] prepared polyethylene glycol and turmeric nanofibers (TNF)-based nanocomposite. The TNF was used as reinforcement in gum arabic (GA) and maltodextrin (MDX). The nanocomposites have been prepared through a multi-step process. Figure 2 shows the reinforcement effect of the TNF nanofibers in the PEG matrix and GA and MDX matrices. The TNF was loaded in 1–7 wt.% contents in PEG and other matrices using a solution blending method. The PEG-TNF nanocomposite has shown fine nanoparticle dispersion and interfacial adhesion through hydrogen bonding interactions. The TNF nanofiller loading up to wt.% was found to enhance the tensile strength and Young's modulus of the nanocomposites to 5.12 MPa and 49.36 MPa, respectively. The neat matrix has lower tensile strength and Young's modulus of 1.84 and 19.76 MPa, respectively. Moreover, the PEG-TNF nanocomposites revealed fine antibacterial activity against Escherichia coli, Staphylococcus aureus, and other bacterial strains. The TNF nanofillers were found useful for creating a reinforcement effect and interfacial interactions in the nanocomposite matrix, thus increasing the overall mechanical properties. Hence, the PEG-TNF nanocomposites were effective in improving the mechanical properties and antibacterial activity for the relevant uses.

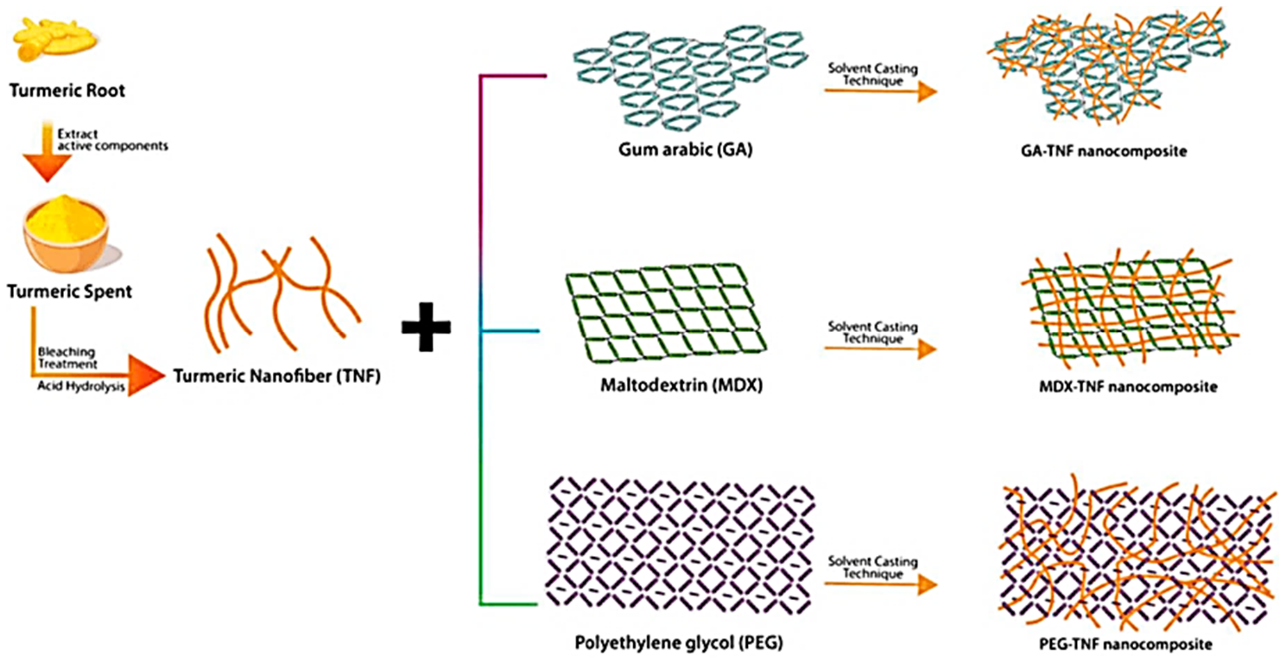


Figure 2. Schematic of the preparation steps for turmeric nanofiber-based nanocomposites [64]. Reproduced with permission from Elsevier.

Poly(lactic acid) (PLA) is also a natural green polymer [65–67]. It is biodegradable polyester gotten from starch. Krikorian et al. [68] developed green nanocomposite based on PLA and nanoclay nanofillers. The green PLA/nanoclay nanocomposites have fine biodegradability, crystallinity, and storage modulus properties. The XRD patterns were used to study the effect on the organoclay crystallization within the PLA matrix. Moreover, the storage modulus of the nanocomposites was found to vary with different nanoclay loadings in the range of 20–150 °C. The storage modulus for 15 wt.% nanoclay loading was enhanced by 61.4%, relative to neat PLA. Wang et al. [69] prepared poly(lactic acid) and nanocellulose crystal (NCC) based poly(lactic acid)/nanocellulose crystal (PLA/NCC) nanocomposite. Neat PLA had a tensile strength of 41.9 MPa, while NCC inclusion enhanced the property up to 53.9 MPa. Table 2 shows the crystallinity results for the PLA/NCC nanocomposite. The XRD analysis of PLA and NCC has shown an increase in the crystallinity of the polymer with the nanofiller loading. The neat PLA had crystallinity of 32.6%. The 2 wt.% NCC has shown the highest crystallinity of 37.8% among the nanocomposite samples. The increase in the crystallinity of the nanocomposite with the NCC loading was due to better alignment and packing of the nanocellulose crystals in the polymer matrix, thus causing the crystallinity.

Table 2. The crystallinity of PLA and PLA/NCC [69]. PLA = poly(lactic acid); PLLA/NCC = poly(lactic acid)/nanocellulose crystal. Reproduced with permission from Elsevier.

	PLA	1 wt.% NCC	2 wt.% NCC	3 wt.% NCC	4 wt.% NCC
% Crystallinity of PLA	32.6	37.3	37.8	35.7	34.1

Li et al. [70] also formed poly(L-lactic acid) (PLLA), PEG, and cellulose nanocrystal (CNC)-based PLLA/PEG/CNC bionanocomposites. The CNC was used to enhance the crystallization behavior of the PLLA/PEG/CNC nanocomposites. Figure 3 shows the crystalline morphology of the pristine PLLA and PLLA/PEG/CNC nanocomposite. The low crystallinity was observed in the neat PLLA matrix with few spherulites. In the PLLA/PEG matrix, the inclusion of CNC enhanced the interfacial interactions between the polymer and the nanofillers and also the crystallinity. Consequently, the crystallinity promoted the formation of convoluted paths in the nanocomposites. The diffusion of the molecules and permeation through the system were enhanced through the nanocomposites.

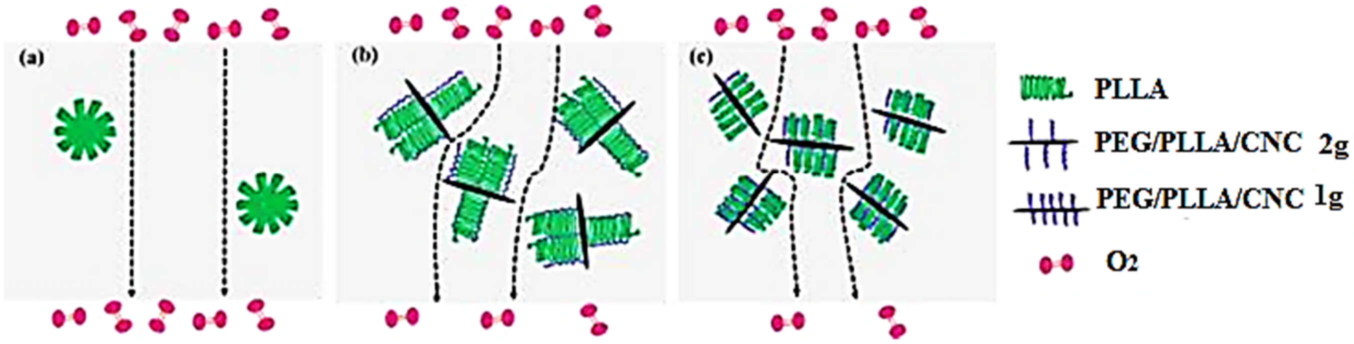


Figure 3. Schematic representation showing crystalline morphological features in (**a**) neat PLLA; (**b**) PLLA/PEG/CNC with 2 g nanofiller; and (**c**) PLLA/PEG/CNC with 1 g nanofiller governing oxygen permeation. The lines represent the diffusion paths of O_2 [70]. PLLA = poly(L-lactic acid); PLLA/PEG/CNC = poly(L-lactic acid) (PLLA)/poly(ethylene glycol)/cellulose nanocrystal. Reproduced with permission from Elsevier.

Poly(vinyl alcohol) (PVA) is a green eco-polymer. It has fine biodegradability and water solubility. Ibrahim et al. [71] prepared PVA and carboxymethyl cellulose-based nanocomposites. The green nanocomposites have also been used for wound healing and non-toxicity applications [72]. Zhao et al. [73] developed PVA and carboxymethyl chitosan (CMC)-based green matrix filled with silver nanoparticles. The PVA/CMC has shown antibacterial properties. Morsi et al. [74] also designed a PVA/CMC green matrix filled with Au nanoparticles. The green PVA/CMC nanocomposites have fine electrical conductivity and dielectric permittivity to be employed for microelectronic devices.

Green nanocomposites based on starch and nanofillers have been reported [75]. Starch is also an eco-polymer, which has been used with nanofillers [76,77]. Kaushik et al. [78] formed starch and cellulose nanofibrils-based nanocomposites. These nanofibrils were dispersed in a starch matrix via a Fluko high shear mixer. The reinforcing effect of the nanofillers was observed. Neat matrix has a tensile modulus of 76 MPa, whereas a 15 wt.% loading enhanced the property to 224 MPa. Cheviron et al. [79] prepared starch and silver nanoparticles-based nanocomposites. Such green nanocomposites have been used for packaging, antimicrobial, and sensing applications. Lignin is a significant engineering eco-polymer gained from the natural sources [80–82]. Lignin and lignin fibers both have been used in the green materials [83–85].

3. Energy Applications of Green Nanocomposites

Initially, the eco-nanocomposites have been used in the fabrication of turbines [86–88]. The turbine blades were constructed using natural composite having high strength, low cost, and lightweight. Despite the traditional composites for wind turbine blades such as metal and epoxy materials, natural composites based on green polymers and hybrids have been used [89]. Afterward, bio-polymer-based nanocomposite has been used in the optoelectronics industry [90–92]. The eco-polymer-derived donor-acceptor structures have been prepared for photo energy conversion [93,94]. Eco-polymers have been used in light-emitting diode devices (LED) [95–97]. Chen et al. [98] primed a polydimethylsiloxane (PDMS) and zinc sulfide (ZnS)-derived LED. The ZnS nanoparticles were used as green nanofillers in LED. The PDMS/ZnS-based green nanocomposite has shown a fine luminescence spectrum. The ZnS nanoparticles were also used in solar cells as sustainable nanofiller. Thus, the solar cell devices have also incorporated green nanocomposites [99–101]. Ghosh et al. [102] formed poly(vinylidenefluoride-*co*-hexafluoropropylene) and platinum nanoparticles-based green materials for solar cells. The platinum nanoparticles were used in an optimum amount in the green matrix in solar cells. The poly(vinylidenefluoride-*co*-hexafluoropropylene)/platinum nanoparticle showed an open-circuit voltage of 2.7–23 V and short-circuit current of 2.9–24.7 µA. Zhang et al. [103] designed green nanocomposites-based energy conversion devices i.e., thermoelectric generators. The organic polymers-based thermoelectric materials were used for green energy conversion. Most importantly, polyanilines, polypyroles, polythiophenes, and poly(3,4-ethylenedioxythiophene) have been used. Recently, bio-based conducting polymers and nanocomposites have been adopted in the photovoltaics and optoelectronics industries [104,105]. The inclusion of green nanofillers in p-type conjugated polymers may develop donor-acceptor heterostructures for photo energy conversion [106]. In this regard, Zhuang et al. [107] investigated the photophysical properties of the green conjugated polymer-based materials. Green composites have been useful in these devices to improve eco-friendliness and steadfastness [108]. Concisely, the green nanocomposites have found solicitations in various areas of the energy sector such as optoelectronics, supercapacitor, nanogenerators, and other electrical devices.

4. Energy Storage Using Green Nanocomposites

Research has been turned towards consistent electrical energy storage resolutions [109,110]. There are several electrical storage practices that have been adopted for chemical, magnetic, or electrical energy storage such as batteries, solid oxide fuel cells (SOFCs), superconducting magnetic energy storage (SMES) devices, and electrostatic/electrochemical capacitors [111–113]. Among all these systems, capacitors have been found reliable for a reasonable cost, low operating voltage, high power density, and sweeping applications [114]. To present the comparison of different energy storage devices, a Ragone plot is given in Figure 4. Different energy storage devices have their individual characteristic times [109]. The capacitors have fairly high power density and charge/discharge rates relative to SOFCs and batteries. The capacitors have been applied in electronic circuits, electrical vehicles, power systems, and green energy storage systems. The supercapacitor is a significant type of capacity energy storage device [115–117]. To improve eco-friendliness, green nanocomposites and nanomaterials have been used in supercapacitors. In this regard, green synthesis methods have been adopted to form nanocomposites. However, to develop the purely green nanocomposites, mostly green polymers, and green nanofillers have been used. Several attempts have been made towards the formation of nanocomposites using the green method. Çıplak et al. [118] prepared polyaniline (PANI), graphene oxide (GO), reduced graphene oxide (rGO), and gold (Au) nanoparticle-based GO-Au@PANI and rGO-Au@PANI nanocomposites. Figure 5 shows the formation of rGO-Au@PANI nanocomposite using the green method. Initially, GO was converted to rGO. Then, the Au nanoparticles and aniline monomer was adsorbed on the surface of rGO. The Au@PANI was formed in situ. The polyaniline was deposited consistently on the rGO nanosheet surface through in situ polymerization. The electrostatic interactions existed among the gold nanoparticles and rGO nanosheet. The π-π interactions existed among the PANI and rGO. The pristine PANI, GO-Au@PANI, and rGO-Au@PANI nanocomposite electrodes have a specific capacitance of 17.6, 42.5, and 63.5%, respectively. Figure 6 shows the dependence of the specific capacitance on the scan rate of the nanocomposites. The rGO-Au@PANI nanocomposite had high specific capacitance of 212.8 Fg^{-1} at current density of 1 Ag^{-1}.

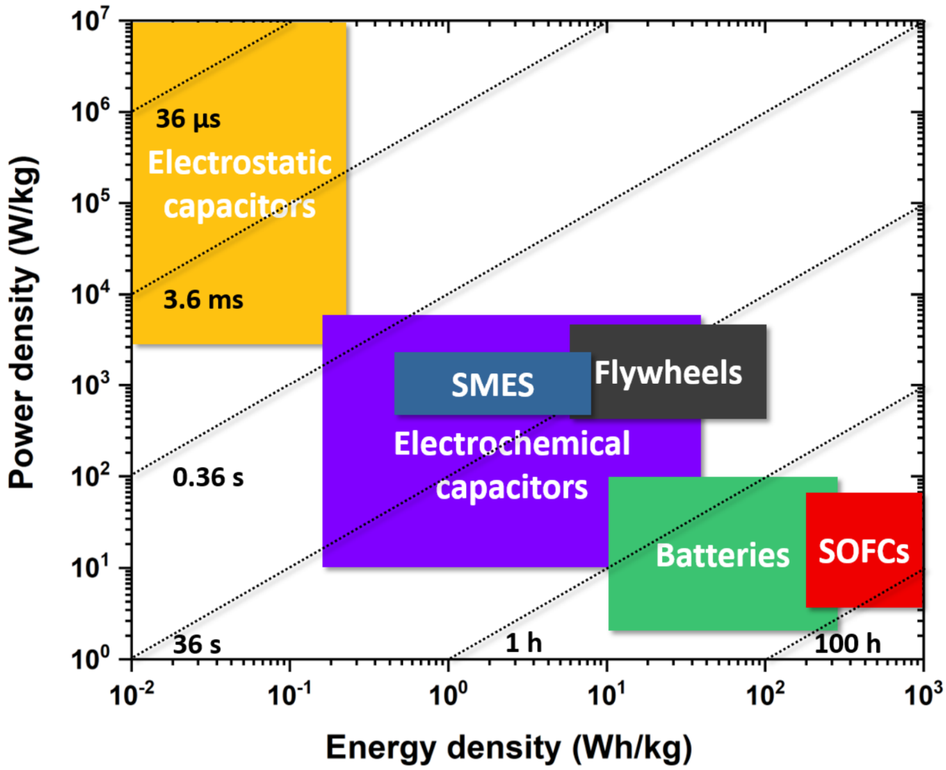


Figure 4. Ragone plot of different energy storage devices: electrostatic capacitors, electrochemical capacitors, SMES flywheels, batteries, and SOFCs [119]. SMES = superconducting magnetic energy storage; SOFCs = solid oxide fuel cells. Reproduced with permission from Elsevier.

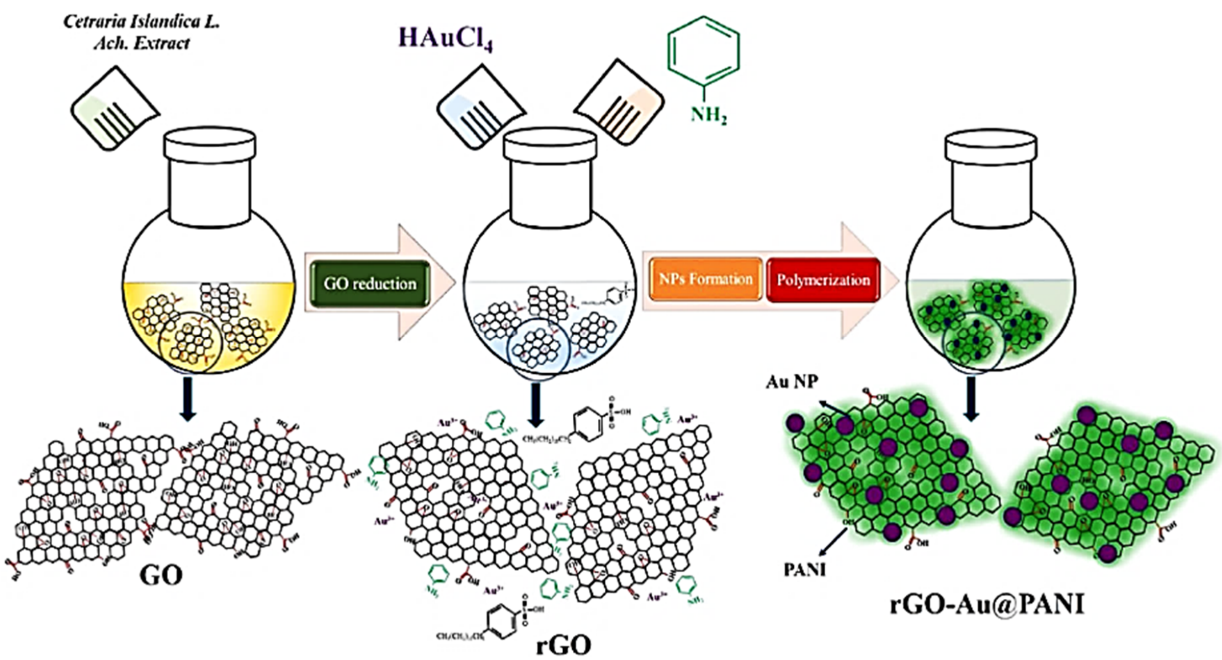


Figure 5. Schematic representation of the preparation of rGO-Au@PANI nanocomposite [118]. rGO-Au@PANI = reduced graphene oxide-gold nanoparticle@polyaniline. Reproduced with permission from Elsevier.

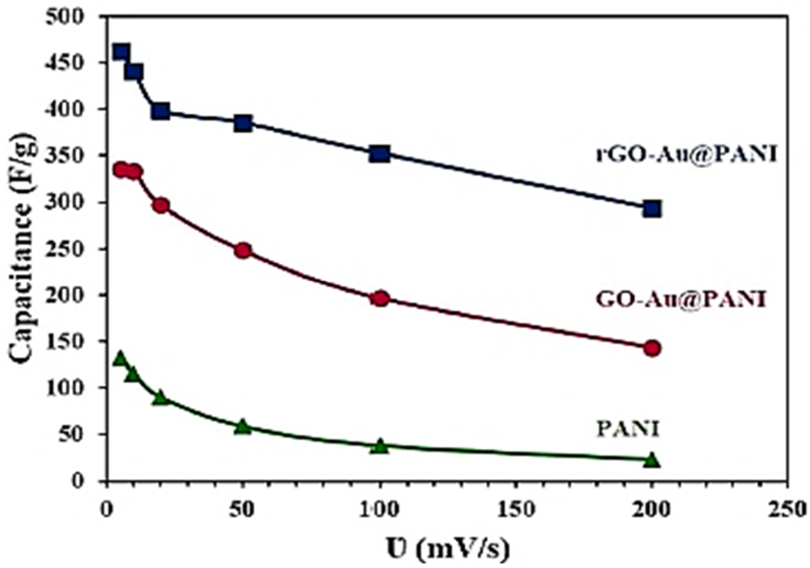


Figure 6. Dependence of specific capacitance on the scan rate (5–200 mVs^{-1}) for pristine PANI, GO-Au@PANI, and rGO-Au@PANI [118]. PANI = polyaniline; GO-Au@PANI = graphene oxide-gold nanoparticle@polyaniline; rGO-Au@PANI = reduced graphene oxide-gold nanoparticle@polyaniline. Reproduced with permission from Elsevier.

Arthisree et al. [120] prepared graphene quantum dot (GQD) doped polyacrylonitrile (PAN) and polyaniline-based PAN/PANI@G nanocomposite. Figure 7 shows the prototype supercapacitor composed of PAN/PANI@G prepared using the green method. The nanocomposite electrode with 1.5 wt.% GQD was formed by sandwiching the PAN/PANI@G between NaCl solution and aluminium foil. The supercapacitor had 1.4 V output power for 60 min working time. The PAN/PANI@G nanocomposite with 1.5 wt.% GQD has shown high specific capacitance. The specific capacitance was found in the range of 105–587 Fg^{-1}. The capacitance values were found higher than the neat polyaniline-based supercapacitor electrode [121]. Green approaches have been used to incorporate the inorganic nanoparticles in nanocomposite electrodes [122,123]. Chakraborty et al. [124] primed styrene-maleic anhydride copolymer and ZnO nanoparticle-based nanocomposite for a supercapacitor.

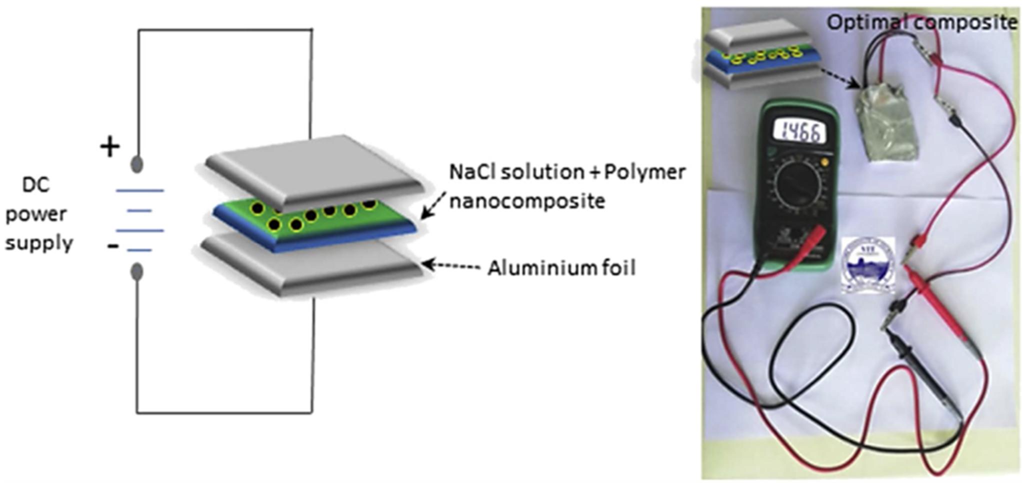


Figure 7. Illustration for PAN/PANI@G 1.5 wt.% based supercapacitor and its typical digital photograph of optimal nanocomposite verified for voltage generation [120]. PAN/PANI@G = polyacrylonitrile/polyaniline/graphene quantum dot. Reproduced with permission from Elsevier.

Figure 8 shows the specific capacitance of the nanocomposites with varying current densities. The specific capacitance was increased from 145 Fg^{-1} to 268.5 Fg^{-1}. Ceramic nanofillers like $BaTiO_3$ have also been used in the nanocomposite electrodes [125]. High-performance supercapacitors have been designed using high electrical conductivity, consistency, and optimum processing parameters. In this regard, novel nanocomposites need to be used to fabricate supercapacitors for integrated circuits and other devices.

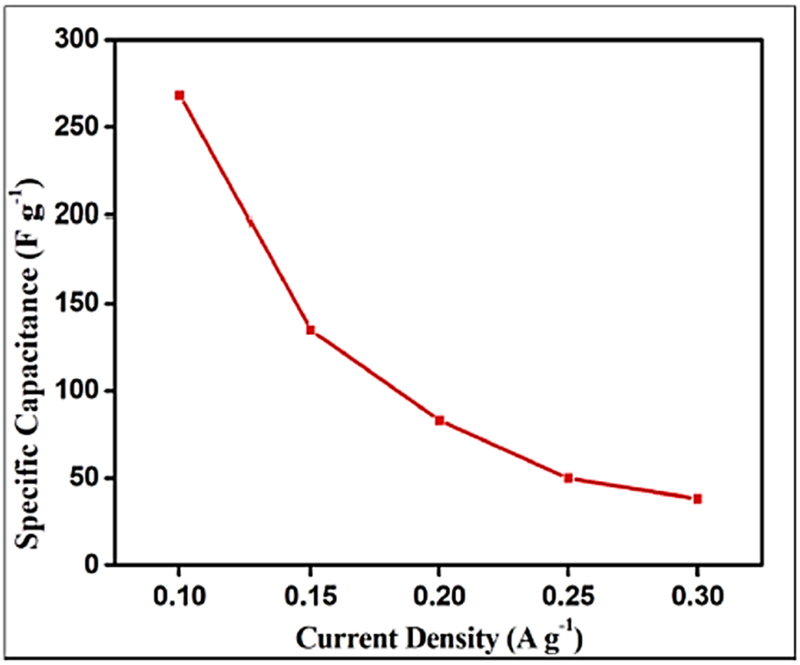


Figure 8. Specific capacitance versus current density of nanocomposite at 0.1 Ag^{-1}. (0.1 g ZnO nanoparticles) [124]. Reproduced with permission from Elsevier.

As discussed above, carbon materials (carbon nanotube, graphene, etc.) and conducting polymers have been commonly used for the supercapacitor electrodes [126]. Along with the conducting polymers and carbon nanomaterials, the transition metal oxides or hydroxides such as NiO, MnO_2, $Ni(OH)_2$ have also been used. To make the electrode materials green, one method is the use of regenerated cellulose aerogel [127]. The regenerated cellulose aerogel has also been prepared in combination with graphene oxide. Thus, the green supercapacitor electrodes consist of both cellulose aerogel and graphene oxide. The supercapacitors with green electrodes of the regenerated cellulose/graphene oxide aerogel have shown the moderate specific capacitance of 71.2 Fg^{-1}. Furthermore, it is essential to incorporate the conducting polymers in the regenerated cellulose/graphene oxide aerogel to improve the specific capacitance of the devices [128]. Thus, the graphene oxide and conducting polymers have been converted into green electrically conductive aerogels [129]. A very common method is to mix the GO solution with the solution of cellulose and conducting polymer. In another study, Tian et al. [130] prepared the green nanocomposites through the in situ polymerization of aniline monomer on porous cellulose scaffolds. Later, the Ag nanoparticles were deposited on the green electrodes using the electrodeposition process. Zu et al. [131] formed green electrodes using high surface area carbon and cellulose aerogels. The pyrolysis method was used. The electrode with porous interconnected nanostructure had revealed a high capacitance of 1873 $m^2\ g^{-1}$. The aerogel had specific capacitances of 302 Fg^{-1}. Yang et al. [132] used bamboo cellulose fibers with the regenerated cellulose and formed aerogel-based green electrodes. The high specific capacitance of 381 Fg^{-1} was attained. Besides, the cellulose aerogels have been doped with nitrogen or sulfur to enhance the capacitance properties of the green supercapacitor electrodes [133,134]. The cellulose has also interacted with the metal oxides, metal hydroxides, and conducting polymers to form green electrodes [135]. There is a need for the introduction of metal or carbon nanoparticles in cellulose to decrease the rigidity of the aerogels. Several attempts have been made on the use of biomaterials-derived green electrodes for supercapacitor application [136]. Table 3 shows green electrode-based supercapacitors derived from biomaterials. The supercapacitors had high flexibility, cyclability, and good specific capacitance of up to 330 Fg^{-1}. However, the green nanocomposite electrodes need to be further researched to enhance the physical characteristics, capacitance, charge density, and electrochemical properties to meet the necessities of high performance supercapacitor electrodes.

Table 3. Performance of green supercapacitor electrode materials.

Green Material	Specific Capacitance (Fg^{-1})	Reference
Conjugated polymer	212.8	[118]
Conjugated polymer	105–587	[120]
Synthetic co-polymer	145–268.5	[124]
Cellulose	71.2	[127]
Conjugated polymer	302	[131]
Cellulose	381	[132]
Doped cellulose	>100–300	[133,134]
Starch	168	[137]
Starch	304	[138]
Gelatin	183	[139]
Cellulose	242	[140]
Cellulose	330	[141]
Carbohydrate	213	[142]
Carbohydrate	300	[143]

5. Advantages/Disadvantages of Green Nanocomposites in Energy Storage

The use of non-green electrodes in supercapacitors may involve environmental pollution, material degradation, high chemical consumption, high toxicity, and high cost. On the other hand, the benefits of using green nanocomposites in energy storage devices are environmental friendliness, high stability of material such as cellulose, electrode preparation at room temperature, and no use of harmful or toxic solvents. Such nanocomposite electrodes have a high dissolving capacity of green materials, insignificant volatility, structural tunability, non-flammability, recoverability, high recycling rate, high capacitance, and high mechanical properties. However, there are some disadvantages of green nanocomposites in energy storage devices. First of all, the capacitance of pure green nanomaterials is often low. There is a need to increase the capacitance of the green electrodes using the non-green conducting polymers and nanocarbons. Some hybrid nanostructures have been prepared using cellulose and graphene oxide nanomaterials. Fewer combinations of nanocarbons with green nanomaterials have been identified so far. The most successful one is the amalgamation of cellulose with the graphene derivatives and conducting polymers. The essential understanding of the structure-property relationships of various types of green polymers and green nanofillers for supercapacitors is valuable. Research in green supercapacitors is an emerging and promising field awaiting future attention.

6. Future and Summary

Effectual electrical energy storage resolutions are keys to future electricity generation problems. The capacitors or supercapacitors have wide-ranging applications in renewable microwave devices, energy storage devices, electronic circuits, electrical vehicles, telecommunication, and other maneuvers and systems. Application fields of capacitors are given in Figure 9. The green nanocomposites prepared renewable resources and through green strategies have been researched for anticipated physical properties, low cost, and facile processing [144]. For high-performance applications, green nanomaterials must have fine morphology, crystallinity, electrical conductivity, thermal stability, and mechanical strength.

In this regard, better structural interactions and compatibility of the nanocomposites are essential [145–147]. The use of green nanofibers such as chitosan, lignin, starch, cellulose, and nanocarbon-based nanofillers in the green polymers may improve the nanocomposite performance for future solicitations [148,149]. Green materials have been continuously applied in supercapacitors to enhance reliability and charge storage performance. Several approaches have been applied to advance the performance of supercapacitors. The enhancement of the dielectric properties and capacitance may decrease the strength properties of the green nanocomposites. Thus, the interactions in the nanocomposites need to be improved to enhance the charge storage mechanism and energy density of these materials. Aggregation may cause problems in the nanofillers dispersion, nanocomposite formation, and the extent of the electric field generated in the green matrix. Interactions among the matrix and the nanofiller may be electrostatic, covalent interaction, hydrogen bonding, and other interactions form the homogeneous nanocomposites. The comprehensive attempts on the high-performance of green nanomaterials are desirable to exploit the true energy storage potential of these materials [150,151].

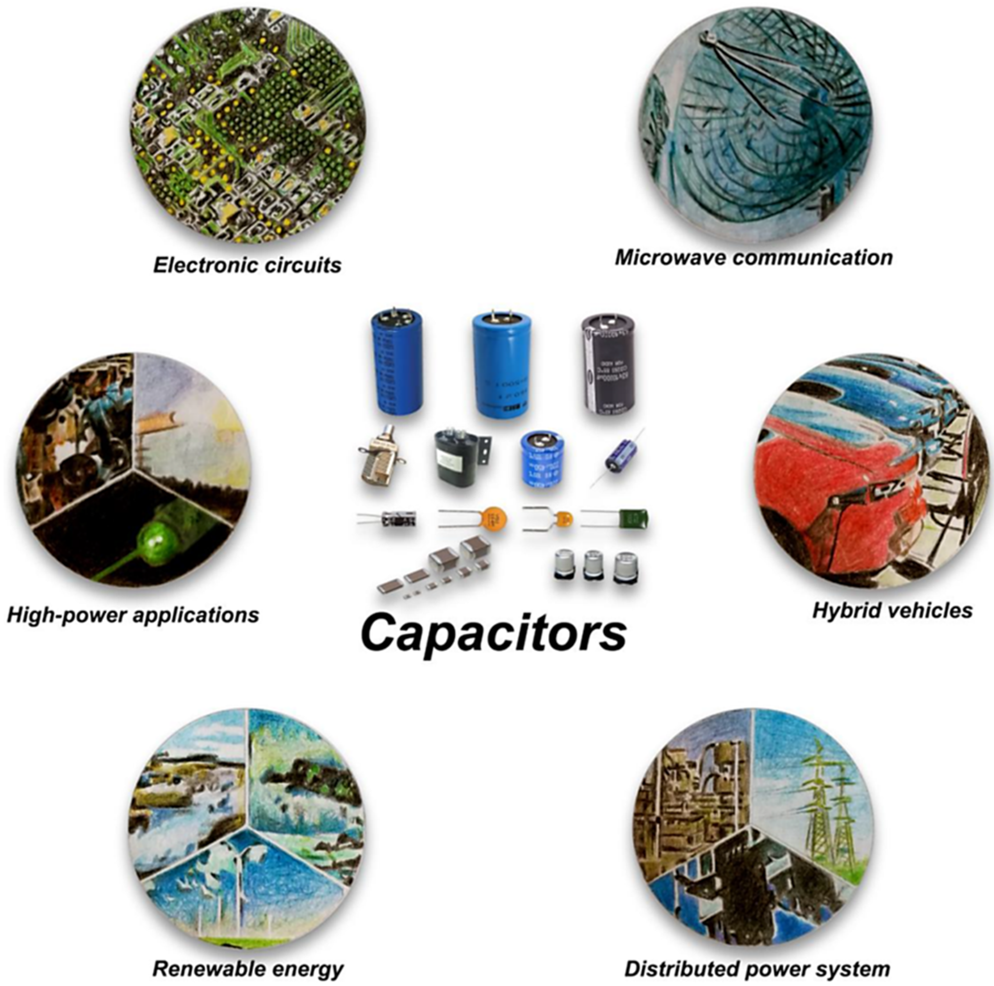


Figure 9. Application fields of capacitors [119]. Reproduced with permission from Elsevier.

This review states the development in the field of green nanocomposites for energy storage applications. The inclusion of eco-nanofillers in eco-polymers has led to high-performance green nanocomposites. The energy performance of green nanocomposites depends on the selection of green polymer matrices, eco-nanofiller, and green synthesis methods. The energy storage properties are reliant on the morphology, crystallinity, matrix-filler interaction, electrical conductivity, dielectric properties, capacitance, charge density, charge/discharge ratio, and several other advanced features. The technical applications of green polymeric nanocomposites have been experiential for energy devices including solar cells, electronics, LED, nanogenerators, and energy storage devices such as capacitors and supercapacitors.

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