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Perovskite and Polymer Composites for High-Performance Supercapacitor Electrodes: A Review

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Abstract

Supercapacitors, which are a prominent type of energy storage device, have attracted considerable interest because of their exceptional power density, rapid charging rate, and extended cycle life. This review explores the composition and fundamental characteristics of perovskite materials, emphasizing their distinct abilities to transport both electrons and ions. Furthermore, they demonstrate a remarkable level of compatibility with electrochemical energy storage devices. The research examining different types of perovskite electrodes, including la-perovskites, Sr-perovskites, Ce- perovskites, and other perovskite oxides, has demonstrated that when combined with conducting polymers like PANI and polyazulene, they form perovskite-polymer composite materials.Electrochemical features, including high specific capacitance, cycle capabilities, and energy and power densities, make these composites valuable. Thus, they are the most promising materials in this field. Their use in supercapacitors is interesting. This research investigates the manufacturing and evaluation of these composite materials. The benefits of approaches such as the one-pot approach and the two-stage electrodeposition process are of specific relevance. The study provides an in-depth analysis of the challenges and technological obstacles encountered in perovskite-polymer composites for supercapacitors, specifically regarding limitations in conductivity and concerns regarding stability. It also discusses the strategies being employed to address these issues. The article offers a comprehensive outlook on the subject of perovskite and polymer composite materials, which have the potential to be used in the development of high-performance supercapacitors. It highlights their capacity to revolutionize energy storage technology and contribute to the progress of effective and environmentally friendly energy solutions.

Keywords: supercapacitor; perovskite; polymer; energy storage; composite

1. Introduction

Novel energy storage equipment with high energy density and good stability are needed due to the increasing use of electronic devices and electric-powered vehicles [1]. Supercapacitors are an emerging energy storage technology known for their exceptional power density, rapid charging capability, and extended lifespan [2]. The electrochemical performance of a supercapacitor is contingent upon the composition of the electrode material, which encompasses metal oxides, carbon-based materials, conducting polymers, and perovskite-based materials [3]. Perovskites with ABX_3 structures have excellent electronic and ionic conduction properties [4]. Nevertheless, there are limitations associated with perovskite materials [5]. One issue is their resistance and the sluggish speed at which charge transfer occurs during electrochemical reactions [6]. The efficiency of active materials is reduced, impacting their performance and capacity [7]. Prior to the utilization of perovskites as high-performance electrode materials in commercial energy storage devices, it is imperative to address and resolve these issues [8]. Improving the electrochemical performances of

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perovskite oxides has involved utilizing different methods such as altering the shape, ion doping, and incorporating other materials. [9,10]. CPs are commonly utilized in SCs due to their widespread availability, affordability, high conductivity, and excellent capacitive performance [10]. Presently, there is extensive research being conducted on p- type conducting systems such as polyaniline, polypyrrole, polythiophene, and its derivatives [11]. PAz, possessing both reversible p–type and n–type doping characteristics and a high theoretical specific capacitance, exhibits great potential as a pseudocapacitive material [12,13].

Perovskite-polymer composites possess unique characteristics that combine the qualities of perovskites with the advantages of polymers [14]. The aforementioned materials are used in advanced energy storage systems, such as supercapacitors [15]. Super capacitors and other energy storage devices benefit greatly from composites as they exhibit distinct electrochemical features [8]. Their precise capacitances have been evaluated at 121 Fg^{-1}, indicating their capacity to store electrical charge [16]. Despite enduring 5000 rounds, these materials maintain 73% of their original capacitance [17]. In addition, they are capable of achieving energy densities of 24.4 Wh kg^{-1}, power densities of 3.9 kW kg^{-1} [18]. Conversely, the electrode-electrolyte interface has exhibited n-type dielectric characteristics, and their mechanical flexibility enables their incorporation into various device structures [19]. Polymers, when included into perovskites, improve their stability and mechanical properties, making it easier for the perovskites to exhibit optoelectronic characteristics such as light absorption and charge transfer [20]. Moreover, polymers provide better ease of processing, allowing the composites to be used in a wide range of optoelectronic devices such as solar cells, LEDs, and sensors, and enhanced processing of large quantities of solid materials [21].

2. Perovskite-Polymer Composite

Combining perovskite oxides with polymeric compounds balances their densities, enhancing energy storage and retaining quick electrochemical reactions [15]. Specific capacitance increases significantly when perovskites are combined with polymers [9]. Polymers absorb ions better due to their increased surface area [22]. By adjusting the ratio of polymer to perovskite, it is possible to precisely control the electrochemical properties, mechanical strength, and stability of the composite material [23]. Perovskite-polymer composites have a higher ability to last longer during various numbers of charge-discharge cycles because of the protective nature of the polymer components against ion insertions and extractions [8]. The ability of the polymer to help maintain its structural integrity throughout a longer period increases the lifespan of the device [24]. More so, the high absorption of photons in the perovskites increases their potential in the production of light-rechargeable supercapacitors [25]. The perovskite layers can absorb photons resulting in electron-hole pairs, increasing the ability of the layer to store an electric charge [6]. The current study has emphasized the prospect of the long-term restorative capacity, the ability to respond with an increased need, and the view of the economic justification [26].

2.1. $CsPbBr_3$–PMMA Composite

A recent research paper thoroughly reviews the numerous benefits and practical uses of Highly Stable and Luminescent $CsPbBr_3$–PMMA Composites [4]. $CsPbBr_3$–PMMA composites are more durable and reliable to repeated exposure [27]. The eco-friendly synthesis approach removes organic solvents from $CsPbBr_3$–PMMA Composite production [28]. The technique is green chemistry-friendly and aims to generate eco-friendly products by lowering environmental impact [29]. The PL intensity was 70% for $CsPbBr_3$–PMMA and 78% for $CsPbBr_3$–PBMA after one month in the air [30]. After 48 hours of immersion, $CsPbBr_3$–PMMA and $CsPbBr_3$–PBMA composites remain extremely water-resistant, with PL intensity remaining at 54% and 56%, respectively [31]. After 30 days in water, the PL spectra's peak form remained consistent, demonstrating stability [32]. The composite demonstrated a remarkable specific capacitance of 528 m Fg^{-1} under the current density of 100 m Ag^{-1}, which shows the ability to store an enormous amount of electrical energy [28]. In addition, the

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composite showed an outstanding repetition capability, making it possible to cycle the material 10,000 times with more than 90% of its initial capacitance [33].

A one-pot synthesis method was employed to create stable and luminous $CsPbBr_3$–PMMA Composite by crystallizing perovskite structures and integrating them into a polymer matrix [34]. First, gas was carefully removed from the monomer solution in nitrogen [30]. It was done to avoid oxygen, which could slow polymerization [14]. The first thermal synthesis of composite perovskite-polystyrene at 70 degrees Celsius produced a yellow semi-transparent product [32]. Methacrylate monomers, which polymerize faster, improved the procedure and styrene monomers have sluggish radical polymerization kinetics [35]. Perovskite- methacrylic polymer composites use methyl methacrylate as the main constituent [36]. Despite MMA's increased polarity, $CsPbBr_3$ was synthesized in bulk methacrylate [37]. A perovskite-PMMA composite, bright with a yellow shade, was obtained after 12 hours at 70 degrees Celsius [38]. Polymerization was initiated in the MMA monomer solution under UV light to accelerate the synthesis process [39]. The one-step synthesis capability of a wide range of easily accessible monomers makes it feasible to create the perovskite-polymer composites framework [30].

The versatile approach works for poly(methyl methacrylate) and polystyrene are ideal for optical applications that demand a wide surface area and luminosity [40]. Stability, flexibility and the brightness of supercapacitors are enhanced with composites [5]. Supercapacitors with $CsPbBr_3$–PMMA composites exhibits superior air stability and water resistance [41]. The composites $CsPbBr_3$–PMMA and $CsPbBr_3$–PBMA show 70% and 78% photoluminescence intensities, respectively, over a month in air [30]. After 48 hours in water, $CsPbBr_3$–PMMA and $CsPbBr_3$–PBMA maintain photoluminescence intensities of 54% and 56%, respectively. $CsPbBr_3$–PMMA composites exhibit exceptional endurance in demanding environments, making them ideal for applications requiring long-term stability [42]. The $CsPbBr_3$–PMMA composite is strong, with 320 MPa tensile stress and 15% breaking strain [43]. The composite is suited for high mechanical stress and moduli applications because to its rigidity and green light emission [30]. The $CsPbBr_3$–PMMA composite exhibits 62.4% photoluminescence quantum yield (PLQY), demonstrating excellent luminosity for various devices [32]. Under various environmental conditions, the $CsPbBr_3$–PMMA composite beats weight-based tests in stability and specific energy density [30].

2.2. Ru-Based Perovskites/RGO Composite

Recent investigations have shown that Ru-based perovskites and reduced graphene oxide (RGO) composites have high specific capacitance [44]. Composites with high energy storage capacities are ideal for high-performance supercapacitors which activated RGO films used to make graphene films exhibit a power density of 500 kW kg^{-1}, energy density of 26 Wh kg^{-1}, current density of 11 A g^{-1}, and specific capacitance of 120 F g^{-1} [45]. Rationalizing further that leveraging mesoporous structures in macro porous frameworks material engineering has allowed one to achieve as much as 3300 m^2g^{-1} specific surface areas [46]. Hereby, rationalized specific surface area is demonstrated to have allowed 339 kW kg^{-1} power densities, 75 Wh kg^{-1} energy densities, and 175 F g^{-1} specific capacitances [47]. To enhance supercapacitor performance, Ru-based perovskites/RGO composites were made utilizing two distinct synthesizing approaches, each with a varying impact [48]. Yang et al. made a long-lasting and conductive RuO_2/RGO composite framework on carbon paper using double-phase synthesizing [49]. Graphene is electrophoretically reduced from chloride when electrochemically deposited on carbon paper, creating RuO_2 nanoparticles that conduct [44]. Atomic layer deposition is used to deposit RuO_2 particles on graphene nanosheets in an orderly pattern and sticks [50]. One of the method's many features is its long-term performance, as shown by electrochemical activity repeated 2000 times [3]. A high specific capacitance of 345 F g^{-1} and even more exciting SC of 1365 Fg^{-1} [48,51]. State-of-the-art three- dimensional network topologies quickly transmit protons and electrons during electrochemical reactions to increase energy generation and release by the supercapacitor which generated Ru-based perovskites/RGO composites [23]. Yang et

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al.'s rigorous two-stage approach produced high- power and energy density RuO_2/RGO nanocomposites on carbon paper [52]. The composites' 92% performance retention after 4000 charge-discharge cycles demonstrated the electrodes' durability [3][53].

Table 1. Specific Capacitance of Ru-Based Perovskites/RGO Composites for Various Synthesis Technique.

Synthesis Technique	Specific Capacitance (Fg-1)	References
Hydrothermal	1585	[54]
Laser scribing method	1140	[55]
Sol-gel and low temperature annealing	570	[56]
Solution phase assembly	480	[57]

Hydrogel electrodes retain supercapacitivity after 2000 cycles [58]. Hydrogels beat traditional counterparts in rate capacity with a specific capacitance of 345 F g^{-1} [59]. One- step hybrid manufacturing boosts specific capacitance by 1365 F g^{-1}, making these composites suitable for high-energy-density applications [60]. The strategy's single application helps after 2,000 rounds, electrodes still work.Durable electrode [61]. By adding RuO_2 to composites, specific capacitance can reach 1365 F g^{-1} [58]. These methods improve capacitance, power, energy density, cycling stability, rate performance, and durability [52].

Durable in repeating applications, new composite materials provide high power and energy efficiency and 92% cycling retention after over 4000 charge-discharge sets [62]. High specific energy density, which measures charge storage capacity, makes these composites appropriate for supercapacitors [3]. The one-step hydrothermal technique produced RuO_2/RGO hydrogels with a high specific capacitance of 1365 F g^{-1}, proving effective charge storage [63]. Additionally, sol-gel-fabricated hydrous RuO_2/graphene sheets with low-temperature calcination exhibited 571 F g^{-1} specific capacitance [64]. These compounds must be explored for supercapacitor technology to improve energy density and stability for future energy storage devices [44,48].

2.3. STO:PANI Composite

Energy storage and discharge devices benefit from Strontium Titanate and Polyaniline (STO:PANI) composites high specific capacitance which have high current densities that maintains 80% capacitance at 20 A g^{-1} current density and cyclic stability strengthens STO: PANI composites [65]. From 1500 cycles at 9 A g^{-1}, the composite retains 70% of its specific capacitance [66]. Since robustness shows a material can withstand repeated charging and discharging without capacity loss, supercapacitors need it [67]. Strontium Titanate-Polyaniline composites were created by chemical polymerization using catalysts of highly tailored counteracted STO particles via aniline cautious oxidation (Figure 1) [14]. The STO particles were initially distributed equally in the aniline monomer and 1M hydrochloric acid while an ice bath was used to reduce the reactivity of the product [68]. For further homogenization following the first phase, a cold solution of ammonium persulfate was added contiguously to the aniline/STO blend and stirred at all times [65]. Autoclaving the reactants overnight at 110° C ensured polymerization after three hours [69]. Filtering and washing with distilled water and acetone removed monomers and oligomers from the post-reaction mixture [65]. This composite was formed by oven-drying the mixture [70]. STO-aniline molar ratios of 2:1, 1:1, and 1:2 were used to study composite attribute variations due to composition [71]. Variations produced composite samples SP21, SP11, and SP12 [72]. Oxidative chemical polymerization improved heterojunctions in STO:PANI composites which enhance contact charge transmission, affecting composite material electrochemistry [62].

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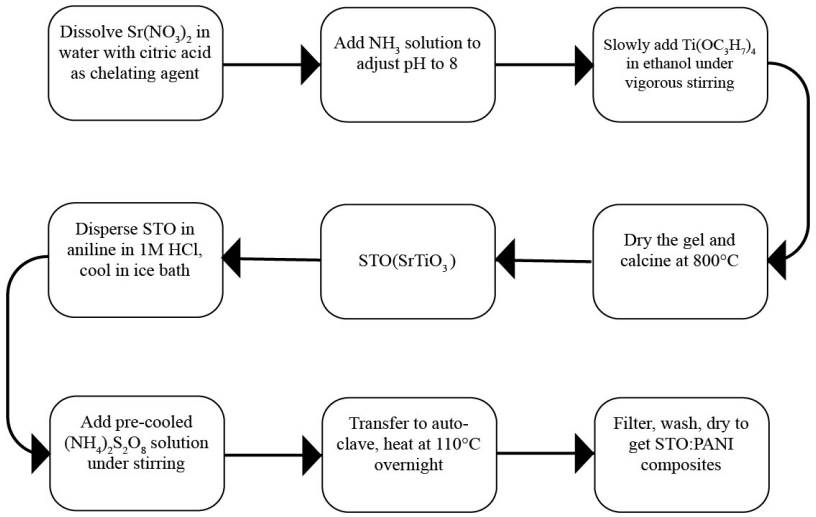

Figure 1. $SrTiO_3$: PANI (STO: PANI) composite preparation Process [73].

The existence of particles and their reduced dimensions on the structure of the composite shows a large surface area and, as a result, increases capacitance values [74]. Additionally, the composites have extraordinary cyclic stability, preserving a constant capacitance value for more than 1500 cycles [75]. The combination of Strontium Titanate and Polyaniline (STO: PANI) provides multiple advantages to the functional properties of supercapacitors [76]. Initially, an improvement in the electrochemical performance is noticed, which can be ascribed to the creation of efficient heterojunctions inside the STO: PANI composites [3,77]. Heterojunctions significantly improve the movement of electric charge across various materials, which is essential for the increase of electrodes' electrochemical efficiency in supercapacitors [78]. Besides, the SP11 composite with a one-to-one ratio of STO to aniline also demonstrates an outstanding increase in specific capacitance [21]. The measured characteristic of 602 F g^{-1} at a current density of 1 A g^{-1} demonstrates that the composite's increased ability to save electric charge has been empirically confirmed [79]. An optimally high specific capacitance is vital for the efficient use of supercapacitor devices in the process of energy storage [80].

2.4. $KCuCl_3$/PANI Composites

$KCuCl_3$/PANI composites have shown promising results in specific capacitance, current handling capacity, and cyclic stability for supercapacitor electrodes [40]. The capacitance is 2434 and 1183 Fg^{-1} for each composition [65]. The composites' capacitive advantage shows substantial charge buildup per mass, suitable for high- performance energy storage devices [18]. The cyclic stability of the $KCuCl_3$/PANI electrodes significantly improved to 97% and 96% after 3,000 charging/discharging cycles, compared to the initial values of 95% and 92%. [81]. The composites consistent conductivity and shape after many treatments could be their significant advantage for long-term use in energy storage devices [40]. $KCuCl_3$/PANI electrodes have high current responsiveness and electrochemical activity with linear sweep voltammetry [82]. Conductivity and resistivity help charge transfer and redox process kinetics for optimal electrochemical behavior [18]. The polyaniline-supported halide perovskite nanocomposite $KCuCl_3$/PANI is synthesized using solvothermal and antisolvent methods at ambient temperatures. [83]. Solvothermal synthesis dissolves a stoichiometric ratio of potassium chloride and copper chloride in dimethyl sulfoxide with hydrochloric acid to prevent precipitate formation [14]. Sonication produces a transparent solution, which forms a slurry when toluene is added [84]. It is followed by autoclaving, electric and filter press operations, washing and filtering, as well as annealing [40]. substances KCl and CuCl are dissolved in dimethyl sulfoxide Kingswine & Pashby, 2000, from which the resulting solution is separated on toluene, and mechanical agitation is performed [85]. In the production of composites based on polyaniline, aniline is dissolved in distilled water, and the resulting dissolution is achieved by adding hydrochloric acid to the required pH [65].

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Ammonium persulfate is created in another solution and gently mixed with the aniline solution and precursory synthesized $KCuCl_3$ [65]. A composite results after polymerization, washing, ethanol treatment, and drying [86].

Supercapacitors made from $KCuCl_3$/PANI nanocomposites solvothermal and antisolvent methods could store energy [65]. Composite electrodes produced with 1.0 M KOH electrolytes boost specific capacitance and cyclic stability [77]. PANI electrodes have a specific capacitance of 1757 F/g and 1297 Fg^{-1} at 5 m Vs^{-1}, surpassing basic electrodes [87]. PANI-enriched electrodes preserve 97% to 96% capacitative integrity after 3000 cycles, enhancing cyclic stability [76]. The PANI-based electrodes 438.12 Wh kg^{-1} specific energy density at 0.2 A g^{-1} current density shows that the $KCuCl_3$/PANI composite stores energy relative to its mass [82]. The composite's energy density outperforms typical materials by mass, making it a promising supercapacitor energy storage alternative [82,88].

2.5. $LaNiO_3$-PAz Composite

Excellent $LaNiO_3$-PAz composite exhibits high specific capacitance (464 F g^{-1} at 2 A g^{-1}), indicating strong charge storage power per unit weight [89]. Even under extreme conditions, this composite possesses capacity, indicating good current handling for $LaNiO_3$-Paz [90]. The $LaNiO_3$-PAz composite remains 91.6% capacitance after 3000 charge-discharge cycles at 50 m Vs^{-1}, demonstrating its longevity for supercapacitor which increased by electric double-layer and pseudocapacitance, and the heterostructure's organic and inorganic components synergize to promote transport of mass and transmission of electrons, ensuring structural and electrochemical stability [18,91]. This makes $LaNiO_3$-PAz composite material suitable for supercapacitors in electric vehicles, portable electronics, and energy renewable technologies, especially in high-power, instantaneous supply and long-term retention applications [77].

The Paz@$LaNiO_3$ heterostructure electrochemical performance is good, with a specific capacitance of 464 F g^{-1} at 2 A g^{-1} and an energy density of 56.4 Wh kg^{-1} [92]. The supercapacitor maintains 91.6% of its initial capacitance after 3000 cycles at 50 mV s^{-1}, demonstrating high cycling durability [90]. Electric double-layer capacitance and pseudocapacitance improve heterostructure supercapacitor electrodes [18]. Sol-gel synthesis of $LaNiO_3$ (Figure 2) and in situ oxidative polymerization of azulene improve energy storage by increasing mass transport and charge transfer between the electrode and electrolyte [90]. Understanding ion-electrode interactions with electrochemical impedance spectroscopy and electrochemical quartz crystal microbalance shows the heterostructure's better conductivity and stability at low charge-transfer resistance and quick mass transfer [93]. Density functional theory simulations show the heterostructure's core properties, including the PAz@$LaNiO_3$ band structure's zero band gap and Dirac cone, which enable high-efficiency energy storage and supercapacitor electrode performance and stability [90].

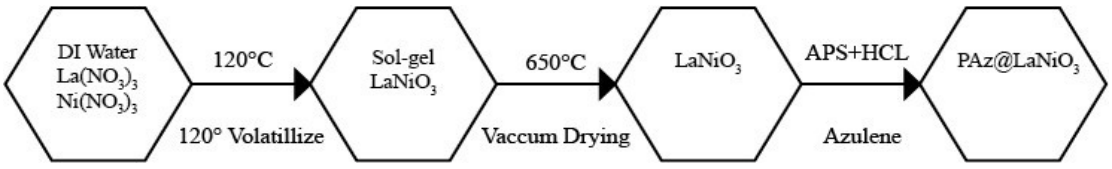

Figure 2. Forming Process of Paz@$LaNiO_3$ [90].

The $LaNiO_3$-PAz heterostructure composite is suited for supercapacitive applications due to its high specific capacitance (464 F g^{-1} at 2 A g^{-1}), energy density (56.4 Wh kg^{-1}), and power density (1100 W kg^{-1}) [94]. The ion dynamics analysis showed that the composite has rapid flux and adsorption capacities, so the measured energy density is a more precise indicator of how much energy can store than its mass, promoting a comprehensive understanding of the remarkable progress in supercapacitive technology development [95].

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2.6. MBI: CPH-G Composite

Highly concede capacitance, current efficiency, and robustness qualify MBI:CPH-G composite as a energy storage supercapacitor [18,78]. The 94.79% capacitors also give the energy that suggests that the performance is a performance post-5,000 charge-discharge cycles for long- term use [96]. Importantly, the light-stored IC interacts with the substrate to store and release more energy than that secreted by capacitive and diffusion arriving dormant [97]. The technological application of this hybrid charge storage is mechanically fitting in many other fields, including substantial energy storage density, charging-discharge capacitance desires, and cycle stability [61].

MBI:CPH-G is made from methylammonium bismuth triiodide in multiple processes [84]. After mixing BiI_3 and MAI in DMF solvent at 1200 rpm and 70 °C overnight, keep the MBI solution in a nitrogen-imbued glove box [98]. Clean FTO glasses using soapy water, deionized water, ethanol, and acetone before MBI solution spin-coating [38]. Symmetric photo-supercapacitors with CPH-G polymer gel electrolytes used dried and heated perovskite sheets as photo-capacitive electrodes [5]. Infrared, absorption, and CPH-G gel electrolyte morphology of MBI photo- capacitive electrodes were examined using Fourier- transform infrared spectroscopy, ultraviolet-visible spectrophotometry, and field emission scanning electron microscopy [99]. Finally, an Autolab PG302N with NOVA 2.1 software characterized MBI:CPH-G photo- supercapacitor energy storage at different scan speeds and lighting conditions [100].

The MBI:CPH-G photo-supercapacitor's dark electrochemical performance includes diffusion and capacitive energy storage mechanisms, according to cyclic voltammetry experiments at various scan speeds [101]. MBI photo-capacitive electrodes rod-shaped structures resembling bars and micro-sheets with a hexagonal shape have nanoporous characteristics that improve capacitive storage dynamics in CV profiles, unlike electric double- layer capacitors rectangular shape [18]. Energy storage is improved by this micro-architecture's electrode and CPH-G gel electrolyte interactions [14]. Light-induced electrochemical charge storage occurs in MBI:CPH-G photo-supercapacitors due to significant UV, visible, and near-infrared light absorption [99]. With a scanning rate of 0.01 Vs^{-1}, photo-generated electron-hole pairs produce a light-amplified areal capacitance of 3.96 mF cm^{-2} and a peak specific capacitance of 4.96 Fg^{-1} [18]. Photographic excitation electrochemical impedance spectroscopy improves light-induced charge storage efficiency by favoring capacitive current over diffusion-controlled current [99][102]. Light improves energy storage, preserving 94.79% of initial capacitance after 5000 charge- discharge cycles, showing cycling stability [90].

Table 2. Specific Capacitance of MBI: CPH-G composite Under Dark and Light environment at various scan rate.

Scan Rate (V s-1)	Specific Capacitance under Dark (F g-1)	Specific Capacitance under Light (F g-1)	References
0.01	0.35	4.96	[99]
0.02	0.26	3.72	
0.05	0.19	2.48	
0.1	0.15	1.65	
0.2	0.11	0.94	
0.5	0.09	0.23	

The nano porous geometry of the MBI:CPH-G composite for supercapacitors allows the electrolyte to access internal surfaces, improving energy storage [86]. This design enhances energy storage by bringing the electrode and gel electrolyte closer together [103]. In terms of energy density, the MBI:CPH-G photo-supercapacitor has areal and gravimetric capacitance values of 0.28 mF cm^{-2} and 0.35 F g^{-1} in dark conditions, but these values increase to 3.96 mF cm^{-2} and 4.96 F g^{-1} in light [95,97]. With a scanning rate of 0.01 V s^{-1}, the energy density increases by almost 1275%, from 0.04 μWh cm^{-2} (0.05 Wh kg^{-1}) in dark conditions to 0.55 μWh cm^{-2} (0.70 Wh kg^{-1}) when illuminated [99]. Cyclic

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charge-discharge stability investigation shows that the MBI:CPH-G photo-supercapacitor retains 94.79% after 5000 cycles, the capacitance has decreased to a fraction of its original value, proving its exceptional performance and reliability [21,97].

2.7. $LaMnO_3$@CC-PPy Composite

The $LaMnO_3$@CC-PPy composite has exceptional electrochemical characteristics, rendering it extremely favorable for advanced supercapacitor applications [104]. The composite demonstrates a remarkable specific capacitance of 862 F g^{-1} at 1 A g^{-1}, which allows for significant energy storage [105]. The composite exhibits consistent performance even under high current densities (up to 10 A g^{-1}) and shows long-term durability with 66% of its capacitance retained after 3000 charge-discharge cycles [106]. The composite's exceptional mix of high capacitance, rate performance, and cycle stability renders it very adaptable for a wide range of energy storage requirements utilizing supercapacitors [74]. The $LaMnO_3$@CC-PPy composite is fabricated by a two-step electrodeposition procedure [84]. Initially, $LaMnO_3$ nanoparticles are applied onto a carbon fabric substrate [94]. Subsequently, a coating of polypyrrole is applied, resulting in the formation of a distinctive nanostructure resembling a coaxial cable [107]. This architecture incorporates two conductive pathways, which greatly improve the movement of electric charges and ions within the substance [108].

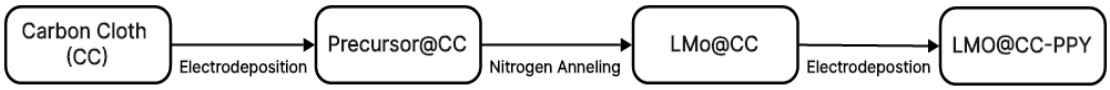

Figure 3. Forming Process of $LaMnO_3$@CC-PPy [109].

The $LaMnO_3$@CC-PPy composite is fabricated by a two- step electrodeposition procedure [109]. Initially, $LaMnO_3$ nanoparticles are applied onto a carbon fabric substrate (Figure 3) [107]. Subsequently, a coating of polypyrrole is applied, resulting in the formation of a distinctive nanostructure resembling a coaxial cable [110]. This arrangement exhibits two conductive channels, which greatly improve the transfer of charge and diffusion of ions within the material [62]. The composite's remarkable electrochemical performance and its applicability for high- performance supercapacitors are dependent on these structural features [111,112]. The synthesis method's efficiency and potential for scaling make the $LaMnO_3$@CC-PPy composite an appealing choice for prospective commercialization [109][113].

The $LaMnO_3$@CC-PPy composite exhibits remarkable energy and power densities (73 Wh kg^{-1} and 800 W kg^{-1} respectively), positioning it as an exceptional choice for asymmetric supercapacitor designs [114]. Nevertheless, researchers must confront the constraints frequently linked to perovskite transition metal oxides, including their diminished conductivity and probable vulnerability in specific electrolyte systems [10]. Effectively addressing these obstacles will be essential in harnessing the complete capabilities of the $LaMnO_3$@CC-PPy composite for real- world supercapacitor uses [9]. Additional research should investigate methods to enhance conductivity by doping or composite modifications and optimize electrolyte compatibility to ensure long-term cycle stability [109].

2.8. $Cs_2AgBiBr_6$-PEDOT: PSS composite

Energy storage systems will also advance from electrochemical enhancements as the specific capacitance is 40% more than the $Cs_2AgBiBr_6$-PEDOT:PSS composite carbon black binary with perovskite electrode [27]. The galvanostatic charge-discharge curves for devices with different energy requirements in order to sample its demand variation potential for relation to current consumption [115]. Its faultless cyclic stability is a strong indicator of its energy storage capabilities, as the P-15 electrode it is composed of retains 97% of its capacitance in 1500 cycles [102]. The $Cs_2AgBiBr_6$-

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PEDOT:PSS composite has a 400 Fg storage capacity, the best dynamic of the charge, and extensive stability, which are favorable improvements to supercapacitors and energy storage [86][116].

Making $Cs_2AgBiBr_6$-PEDOT:PSS composites requires careful planning [61]. A 0.08 M solution of CsBr, $BiBr_3$, and AgBr in HBr is needed to make a lead-free double perovskite powder from $Cs_2AgBiBr_6$ single crystals [27,32]. This solution is heated, stirred, and cooled to pulverize single crystals into $Cs_2AgBiBr_6$ powder [117]. For homogeneity, polyvinylidene fluoride is added to the powder [37]. To make C-15, C7-P7, and P-15 composite electrodes, Carbon Black and PEDOT:PSS are proportionally integrated with N-methyl-2-pyrrolidone solvent according to a methodology [29,86]. PSS into the perovskite electrode, dry the aqueous dispersion, grind it into powder, and mix it with the remaining ingredients [118]. A graphite sheet is covered evenly with a homogeneous slurry [119]. Drying the coated electrode in a vacuum oven at 80° C for 12 hours evaporates solvent and stabilizes it [120].

The specific capacitance and energy density of the $Cs_2AgBiBr_6$-PEDOT:PSS were boosted by synthesis and carbon black and PEDOT:PSS interspersed between porous $Cs_2AgBiBr_6$ electrodes [121]. The binary perovskite-carbon black composites exhibited nearly 40% higher specific capacitance and energy density [61]. The ionic-electronic conductivity balance of the $Cs_2AgBiBr_6$-PEDOT:PSS potentially benefits supercapacitors [122]. The composite will perform well in supercapacitors for maximized energy distribution since the gel echelon showed excellent consistency up to a majority of solid-state symmetric supercapacitor round trips [123].

Carbon black-PEDOT:PSS ternary provides a conductivity-fixing $Cs_2AgBiBr_6$ porous electrode [124]. Specific capacitance and energy density over 40% higher for the carbon black-perovskite electrode binary composite [125]. The quasi-solid-state gel electrolyte solid-state symmetric supercapacitor composite remains after several cycles $Cs_2AgBiBr_6$ is a good energy storage unit and should be utilized since perovskites without it pose environmental and health problems [86]. In charge storage devices, the $Cs_2AgBiBr_6$-PEDOT:PSS composite is limited by technical issues, particularly bismuth-based double perovskites' weak electrical and ionic conductivities [29,97].

Table 3. Specific Capacitance, Current Density and Stability of Discussed Perovskite-Polymer Composites.

Composites	Specific Capacitance (Fg-1)	Current Desnisty (A g-1)	Stability	Ref
CsPbBr3- PMMA	528	100	10,000	[28]
RuO2/RGO	480-1365	11	4000	[48]
STO: PANI	602	1	1500	[73]
KCuCl3/PANI	2434	0.2	3000	[40]
LaNiO3-PAz	464	2	3000	[90]
LaMnO3@CC- PPy	862	1	3000	[109]
Cs2AgBiBr6-PEDOT:PSS	633.5	0.5	10000	[27]

3. Current Situation and Future Research on Perovskite-Polymer Composites

Current studies should focus on prioritizing the advancement of methods to improve the electrochemical characteristics of Ru-based perovskites and RuO_2 (or modified RuO_2) composites, especially when utilizing higher quantities of metal oxide [48]. To achieve progress, it will be crucial to address challenges such as agglomeration, compact morphologies, restricted specific capacitance, and elevated resistance caused by increasing metal oxide loading [126]. Furthermore, it is essential to give priority to the investigation of cost-effective electrode materials that exhibit exceptional energy density and capacitance [111]. This will facilitate the advancement of supercapacitors that are simultaneously more economical and effective [127]. Investigating the charge/energy storage mechanisms of PANI-based halide perovskite composites, studying the influence of hysteresis effects on performance, and analyzing the ion migration inside halide perovskites would provide crucial knowledge for enhancing the field [14,128]. When studying photocapacitors, it is crucial for

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researchers to prioritize improving stability, strengthening energy conversion efficiency, and creating methods to significantly increase capacitance [128]. Additional areas for research could involve examining the integration of EDLC materials to improve the stability of cyclic processes, optimizing dual-purpose electrodes for photo- supercapacitor applications to achieve optimal efficiency, and investigating the potential of lead-free perovskites, specifically bismuth-based variants, for sustainable and eco-friendly energy storage solutions [15]. Combining perovskites with graphene, carbon nanotubes, graphene oxide, or activated carbon enhances electrical conductivity and charge storage [129]. By investigating polymer matrices like conductive polymers or polymer blend topologies, molecular weights, and doping levels, composite characteristics and electrochemical performance can be improved [106]. Studies of perovskite compositions with cesium and formamidinium cations or chloride and bromide anions can increase stability, conductivity, and energy storage [14]. Electrochemical deposition, solvothermal techniques, and vapor-phase deposition can form composite materials with better properties [97]. Combining perovskite-polymer composites with graphene- based supercapacitors and hybrid solar cells improves hybrid energy storage devices [29,86]. Enhancing device topologies and arrangements, employing symmetric and asymmetric supercapacitors, and exploring flexible, stretchy, or integrated energy storage systems can boost these composite uses [3].

4. Conclusions

The study thoroughly analyzes different composite materials for supercapacitors, their substantial progress and potential to revolutionize energy storage technology. The comprehensive examination of perovskite-polymer composites, Ru-based perovskites/RGO composites, STO: PANI composites, and other novel materials demonstrates their remarkable specific capacitance, ability to handle current, and cyclic stability, establishing them as leading contenders in the field of high-performance supercapacitors. Composite materials present a favorable opportunity to improve the efficiency of energy storage, the density of power, and the lifespan of cycles. This addresses the increasing need for dependable and sustainable energy storage solutions in response to the growing number of electronic devices and electric-powered vehicles in today's society. The use of sophisticated synthesis methods, such as the careful two-step procedure for creating Ru-based perovskites/RGO composites and the exact production of $LaMnO_3$@CC-PPy composite, demonstrates the ongoing innovation and commitment to enhancing the efficiency of supercapacitors. These materials possess remarkable properties that make them very suitable for a wide range of energy storage applications, including both portable devices and large-scale grid energy storage systems. Nevertheless, the presence of obstacles like as restrictions in conductivity, worries about stability, and the necessity for additional research and development emphasize the intricate and profound nature of the effort needed to completely exploit the capabilities of these composite materials. Supercapacitor technology is on the verge of making significant gains by tackling these issues with creative methods, state-of-the-art material improvements, and collaborative research endeavors. Further research and advancement in this area will not only propel the advancement of energy storage technology but also facilitate the development of long-lasting, efficient, and environmentally friendly energy storage systems that can meet the changing needs of the future. The favorable attributes of these composite materials, combined with the continuous progress in material design and synthesis methods, are crucial in fully realizing the capabilities of supercapacitors and influencing the development of energy storage technology in a quickly changing world.

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