

Review

# Dispersion Stability of Carbon Nanotubes and Their Impact on Energy Storage Devices

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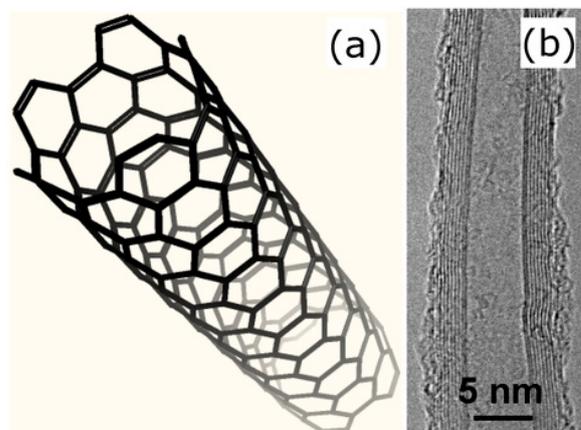
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**Abstract:** Carbon nanotubes (CNTs), with their extraordinary combination of mechanical, electrical, and thermal properties, have emerged as a revolutionary class of nanomaterials with immense potential in energy storage and harvesting devices. Realizing this potential hinges on a fundamental challenge: the dispersion stability of CNTs within various matrices. This review paper provides a comprehensive exploration of the critical interplay between CNT dispersion stability and its far-reaching implications for the performance of energy storage and harvesting technologies. By delving into the underlying mechanisms of dispersion, the strategies to achieve stability, and the direct effects on device functionality, this review sheds light on the intricate relationship between nanotube dispersion and the advancement of energy-related applications.

**Keywords:** carbon nanotubes; dispersion stability; energy storage devices; energy harvesting devices; supercapacitors; batteries

## 1. Introduction

Efficient energy storage solutions are essential for meeting growing energy demands and reducing the environmental impact of human activities [1,2]. To achieve this goal, innovative materials and technologies are being explored and developed [3,4]. Among them, carbon nanotubes (CNTs) have attracted considerable attention due to their outstanding properties at the nanoscale [5–8]. CNTs are one-dimensional nanostructures composed of rolled up graphene sheets (Figure 1), which endow them with extraordinary electrical conductivity, mechanical strength, and thermal properties [6–11]. These qualities make them promising materials for enhancing the performance of various energy technologies.



**Figure 1.** (a) Schematic of a carbon nanotube (CNT), (b) transmission electron microscopy (TEM) image of a CNT showing a number of concentric graphitic walls [6]. Reproduced from ref. [6] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License.



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CNTs have been widely applied in diverse energy applications, such as batteries, supercapacitors, solar cells, and thermoelectric generators [10,12–15]. Their unique electronic and mechanical properties, as well as their versatile structural configurations, enable them to improve the energy conversion and storage processes in these devices. However, a major challenge that hinders the full exploitation of CNTs is their dispersion stability [16–18]. CNTs tend to aggregate due to intermolecular forces, such as van der Waals interactions and  $\pi$ - $\pi$  stacking, forming bundles and agglomerates that compromise their individual advantages [16–19]. Therefore, achieving and maintaining the stable dispersion of CNTs in various matrices is a critical prerequisite for harnessing their potential for energy applications.

The dispersion stability of CNTs is determined by the complex interplay of molecular forces and interactions between CNTs and their surrounding media [20–22]. Various factors, such as CNT type, size, shape, surface chemistry, and matrix composition, affect the dispersion behavior of CNTs [20–22]. To improve the dispersion stability of CNTs, different methods have been developed, such as surface functionalization, surfactant mediation, and novel matrix integration. These methods aim to tailor the interactions between CNTs and their matrices, enhancing both stability and compatibility. The dispersion quality of CNTs can be evaluated using various characterization techniques, such as microscopy, spectroscopy, rheology, and electrochemistry.

In this review paper, we provide a comprehensive overview of the current status and future prospects of CNT dispersion stability for energy applications. We discuss the fundamental mechanisms of CNT dispersion, the factors influencing their dispersion behavior, and the methods to improve their dispersion stability in various matrices. We also review the characterization techniques to assess the dispersion quality of CNTs and their impact on the performance of energy devices. Furthermore, we highlight the recent advances and challenges in applying CNTs for energy storage applications, such as lithium-ion batteries and supercapacitors. By elucidating the intricate relationship between CNT dispersion stability and energy device functionality, we hope to shed light on the state of the art and future directions of CNT-based energy technologies.

## 2. Dispersion Stability of Carbon Nanotubes

CNTs are one-dimensional nanomaterials that consist of rolled up graphene sheets [9]. They exhibit remarkable properties at the nanoscale, such as high electrical conductivity, mechanical strength, and thermal conductivity, which make them attractive for various applications in energy, electronics, and nanomedicine [9,15,23]. However, these properties are often compromised by the poor dispersion stability of CNTs in different matrices. Dispersion stability refers to the ability of CNTs to remain well-dispersed and avoid aggregation in a given medium, such as a solvent, a polymer, or a biological fluid. Dispersion stability is influenced by various forces and factors that affect the interactions between CNTs and the surrounding medium.

One of the key forces that affect the dispersion stability of CNTs is the van der Waals force, which is a weak attractive force between molecules that arises from the fluctuations of their electric dipoles. Van der Waals force is responsible for the formation of CNTs from graphene sheets, but it also causes CNTs to aggregate into bundles and ropes due to their high aspect ratio and surface area [17,18]. The strength of van der Waals force depends on the distance and orientation between the molecules, and it decreases rapidly with increasing distance. Another important force is the  $\pi$ - $\pi$  stacking interaction, which is a specific type of van der Waals force that occurs between aromatic rings, such as those in CNTs [20–22].  $\pi$ - $\pi$  stacking interaction can either enhance or reduce the dispersion stability of CNTs, depending on their alignment, diameter, and chirality. Chirality refers to the twist angle of the graphene sheet that forms the CNT, and it determines whether the CNT is metallic or semiconducting.

Besides these forces, there are other factors that affect the dispersion stability of CNTs, such as hydrophobic effects and geometric factors [17,18,20–22,24]. Hydrophobic effects are related to the polarity of CNTs and the medium. Since CNTs are nonpolar and most

solvents are polar, CNTs tend to avoid contact with the solvent molecules and aggregate together [17,18,20–22]. Nonpolar molecules tend to form clusters in a polar medium as a means to reduce the unfavorable interactions between nonpolar and polar molecules. Geometric factors are related to the shape and curvature of CNTs. The shape and curvature of CNTs can affect the strength of inter-tube interactions and the accessibility of solvent molecules to the CNT surface. For example, single-walled CNTs (SWCNTs) have higher curvature than multi-walled CNTs (MWCNTs), which makes them more prone to bending and twisting. This can reduce the inter-tube interactions and increase the solvation of SWCNTs compared to MWCNTs.

The solubility of CNTs in different solvents is a crucial determinant of their dispersion stability [17,18,20–22]. Solvents that can interact well with the CNT surface can solvate CNTs and prevent them from aggregating. Solvents that cannot interact well with the CNT surface may induce clustering and precipitation of CNTs [17,18,20–22]. The solubility of CNTs depends on the complex interplay between the CNT surface, solvent molecules, and environmental conditions, such as temperature, pressure, pH, and ionic strength [17,18,20–22]. Understanding the dynamics of dispersion stability is essential for developing strategies to improve and manipulate the dispersion of CNTs. Dispersion stability is not only important for preserving the intrinsic properties of CNTs, but also for enabling their applications in various energy devices, such as solar cells, fuel cells, batteries, supercapacitors, and thermoelectrics [6,12,17,18,20–22,25,26].

### 3. Mechanisms and Strategies for Enhancing Dispersion

The realm of enhancing the dispersion stability of CNTs unveils a fascinating landscape where a profound understanding of the underlying mechanisms converges with ingenious strategies, all orchestrated to overcome the challenge of agglomeration and enable the seamless integration of CNTs within various matrices [17,18,20–22]. This section embarks on an exploratory journey into the intricate world of dispersion engineering, unraveling the multifaceted approaches that scientists and engineers employ to tame the dispersion behavior of CNTs and maximize their potential in energy storage and harvesting applications.

#### 3.1. Covalent and Non-Covalent Functionalization

Delving into the heart of dispersion stability strategies, the realm of functionalization emerges as a promising avenue that allows researchers to sculpt the surface properties of CNTs, thereby tailoring their interaction with surrounding media. Functionalization refers to the process of attaching functional groups or molecules to the CNT surface, either covalently or non-covalently, to modify its physical and chemical properties [17,18,20–22]. Functionalization can enhance the solubility, biocompatibility, and reactivity of CNTs, as well as facilitate their alignment, assembly, and integration with other materials. The summary of each functionalization method is presented in Table 1.

**Table 1.** Summary of CNT dispersion stability with various functionalization methods.

Functionalization Type	Materials	Advantages	Disadvantages	
Covalent	Oxidation	Nitric acid or potassium permanganate	Excellent dispersion stability	Toxic process
	Cycloaddition	Aziridines or cyclooctynes	Good dispersion stability	Sensitive reaction results
	Radical addition	UV irradiation or plasma treatment	Easiness of process	Insufficient dispersion stability
	Polymer grafting	Polyurethane, PMMA-OH, or polyvinyl alcohol	Excellent dispersion stability	Complex synthesis process

Table 1. Cont.

Functionalization Type	Materials	Advantages	Disadvantages
Non-covalent	Surfactant wrapping	Sodium dodecyl sulfate (SDS) or Triton X-100	Good dispersion stability, easiness of process
	Polymer wrapping	Polyvinylpyrrolidone (PVP) or polyethylene glycol (PEG)	Excellent dispersion stability
	DNA wrapping	Single-stranded DNA or double-stranded DNA	Good dispersion stability
			Some chemicals are toxic, less stable than other methods
			Reducing electrical properties
			Sensitive synthesis, short shelf life

### 3.1.1. Covalent Functionalization

At the forefront of functionalization strategies stands the realm of covalent functionalization, where chemists and material scientists meticulously design strategies to graft functional groups onto the CNT surface (Figure 2) [27]. This approach not only bestows solubility upon the nanotubes in specific solvents, but also confers them with surface moieties that can engage in specific interactions with matrix materials. Through covalent bonds, nanotube surfaces undergo a metamorphosis, becoming more amenable to dispersion in various media. However, the art of covalent functionalization necessitates careful calibration, as excessive functionalization can disrupt the pristine electronic properties of CNTs, while insufficient modification might not yield the desired dispersion stability.

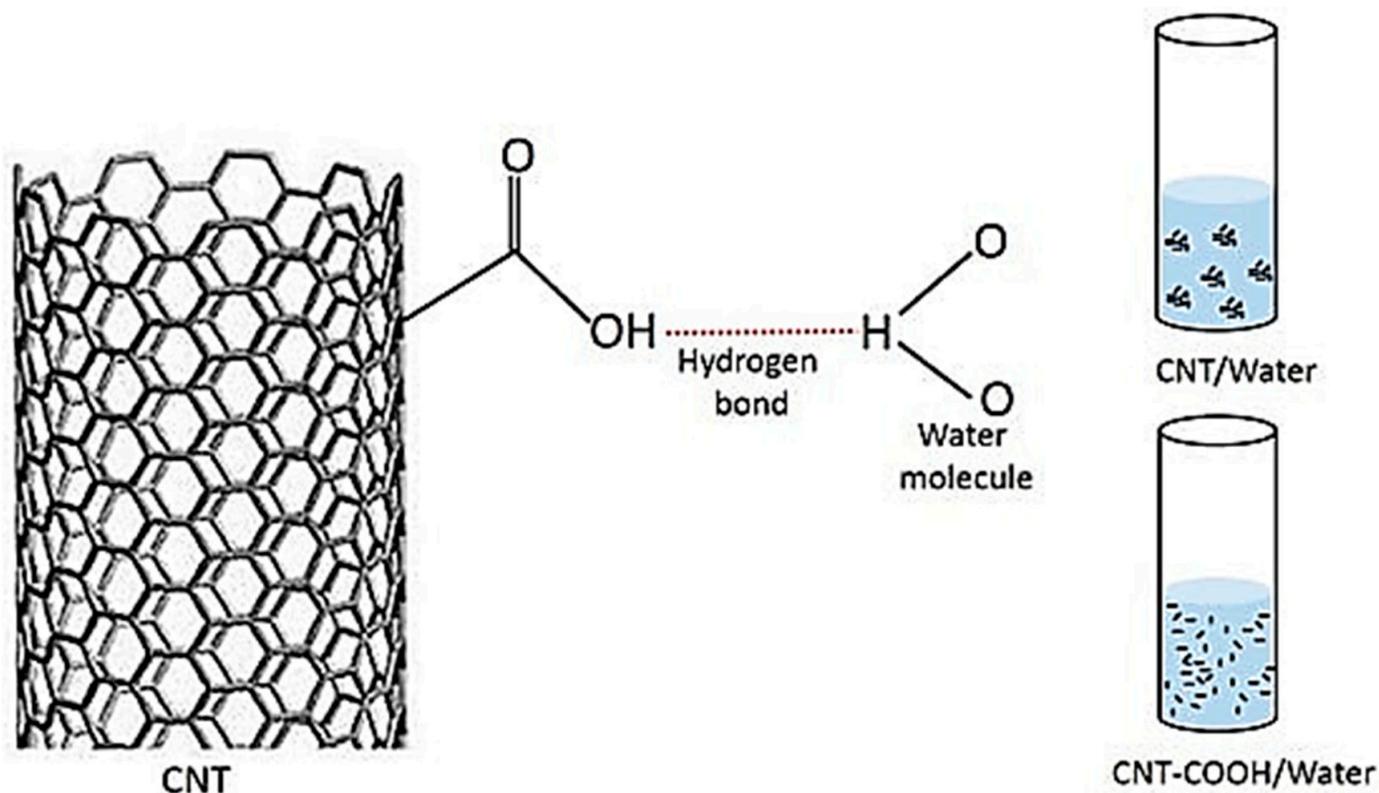


Figure 2. Covalent functionalization of CNTs [27]. Reproduced from ref. [27] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License.

Covalent functionalization can be achieved through various methods, such as oxidation, cycloaddition, radical addition, and polymer grafting [17,18,20–22,28,29]. Oxidation is one of the most common methods for covalent functionalization, which involves treating CNTs with strong oxidizing agents, such as nitric acid or potassium permanganate, to introduce carboxylic acid groups on the CNT surface [17,18,20–22,28,29]. These groups can

then be further modified by coupling reactions with various molecules, such as amines, alcohols, thiols, or biomolecules. Cycloaddition is another method for covalent functionalization, which involves adding cyclic molecules, such as aziridines or cyclooctynes, to the CNT surface through ring-opening reactions. These reactions can introduce various functional groups on the CNT surface, such as amides, esters, or ethers [17,18,20–22,28,29]. Radical addition is a method for covalent functionalization that involves generating radicals on the CNT surface using UV irradiation or plasma treatment [17,18,20–22,28,29]. These radicals can then react with various molecules, such as alkenes or alkynes, to form covalent bonds. Polymer grafting is a method for covalent functionalization that involves attaching polymer chains to the CNT surface by either “grafting from” or “grafting to” techniques [17,18,20–22,28,29]. “Grafting from” involves initiating polymerization from the CNT surface by using initiators that are covalently attached to the nanotubes. “Grafting to” involves coupling preformed polymer chains to the CNT surface by using reactive end groups.

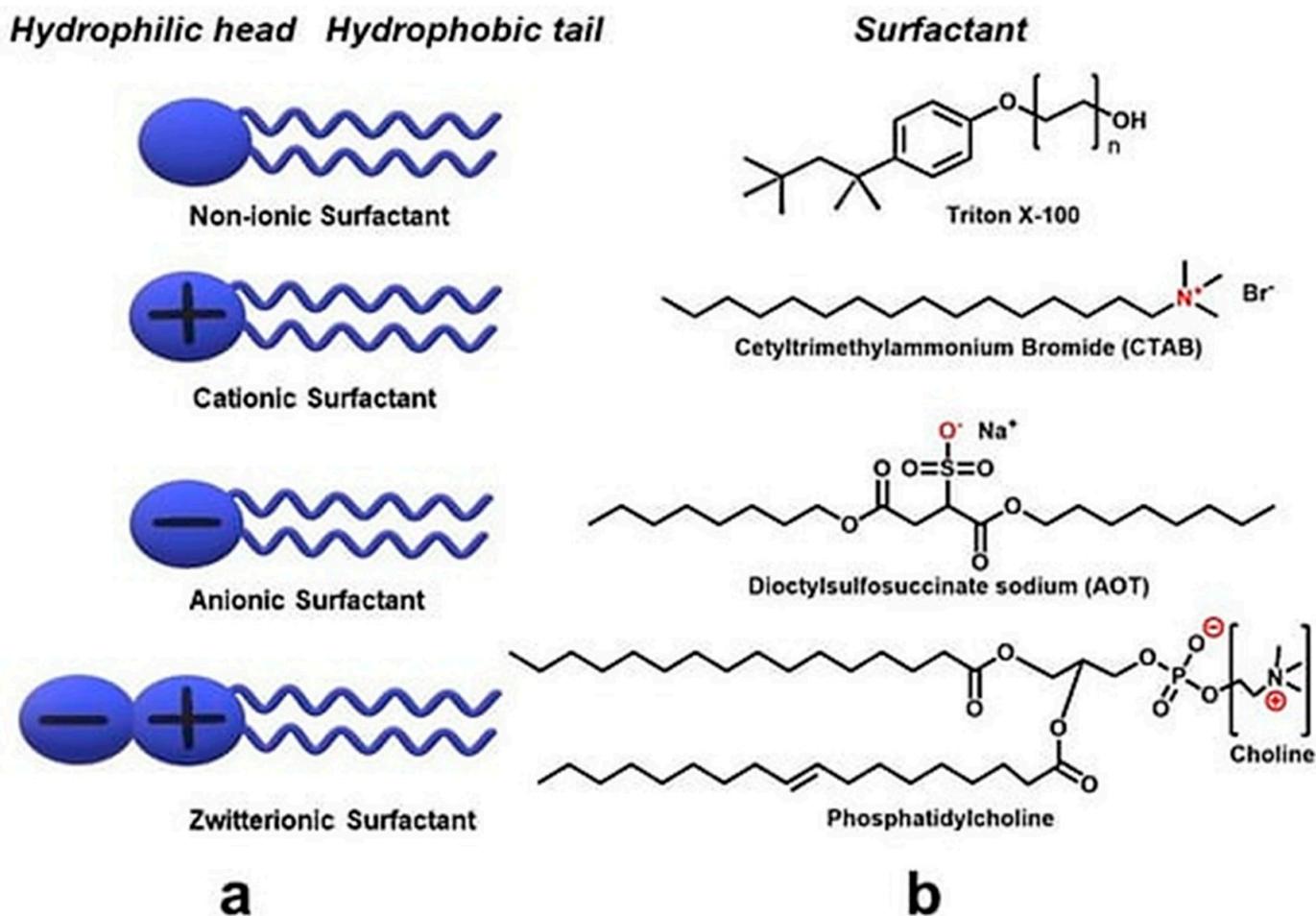
Covalent functionalization can impart various benefits to CNTs, such as improving their solubility in water or organic solvents, enhancing their biocompatibility and bioavailability for biomedical applications, increasing their reactivity and selectivity for catalytic applications, and facilitating their alignment and assembly for device fabrication. However, covalent functionalization also has some drawbacks, such as altering the electronic structure and conductivity of CNTs, introducing defects and impurities on the CNT surface, and affecting the mechanical properties and thermal stability of CNTs.

### 3.1.2. Non-Covalent Functionalization

Non-covalent functionalization, in stark contrast, employs non-covalent forces to introduce molecular entities onto the CNT surface [17,18,20–22,28,29]. These forces include  $\pi$ - $\pi$  stacking interactions, van der Waals forces, and hydrogen bonding [17,18,20–22,28,29]. By strategically designing functional molecules that can interact with the CNT surface through non-covalent interactions, researchers engineer a protective layer around the nanotubes, mitigating agglomeration forces. The versatility of non-covalent functionalization allows for a gentler modification of CNT surfaces while preserving their unique properties, making them amenable to dispersion without compromising their inherent attributes.

Non-covalent functionalization can be achieved through various methods, such as surfactant wrapping, polymer wrapping, DNA wrapping, and biomolecule adsorption [17,18]. Surfactant wrapping is one of the most common methods for non-covalent functionalization, which involves coating CNTs with surfactant molecules, such as sodium dodecyl sulfate (SDS) or Triton X-100 (Figure 3) [17,25]. These molecules can form micelle-like structures around the CNTs, stabilizing them in water or other polar solvents. Polymer wrapping is another method for non-covalent functionalization, which involves wrapping CNTs with polymer chains, such as polyvinylpyrrolidone (PVP) or polyethylene glycol (PEG). These polymers can form a thin layer around the CNTs, preventing their aggregation and enhancing their biocompatibility [12,17,18,25].

Non-covalent functionalization can impart various benefits to CNTs, such as preserving their electronic properties and conductivity, avoiding the introduction of defects and impurities on the CNT surface, maintaining their mechanical properties and thermal stability, and enabling their facile removal and recovery from the matrix [12,17,18,30]. However, non-covalent functionalization also has some drawbacks, such as providing weaker dispersion stability than covalent functionalization, being susceptible to environmental changes such as pH or temperature, and affecting the accessibility and availability of the CNT surface for further modification or interaction.



**Figure 3.** (a) A schematic of different type of surfactants and (b) chemical structures of some common surfactants that have been used in the non-covalent functionalization of CNTs [17,25]. Reproduced from ref. [17,25] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License.

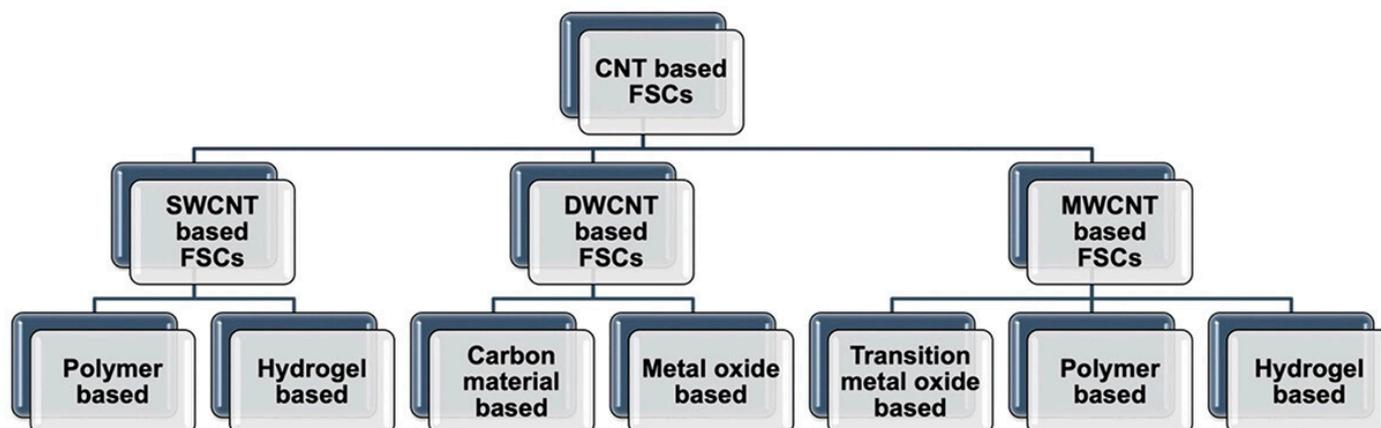
#### 4. Impact on Energy Storage Devices

The profound influence of dispersion stability reverberates far and wide, reaching deep into the realm of energy storage devices, where the performance of critical components such as supercapacitors and batteries is intricately intertwined with the dispersion state of CNTs [31–34]. Within these devices, where efficiency, energy density, and cycle stability are paramount, the careful orchestration of CNT dispersion strategies assumes the role of a master conductor, orchestrating a symphony of performance-enhancing attributes. In this section, we will explore how CNT dispersion stability affects various aspects of electrode performance in supercapacitors and batteries, such as surface area, ion diffusion, charge storage, mechanical stability, electron transport, and energy density. We will also provide some examples of CNT-based electrodes that demonstrate the benefits of dispersion stability in energy storage devices.

##### 4.1. Supercapacitors Enhance Electrode Performance through Dispersion Stability

Supercapacitors are electrochemical devices that store and release energy through the reversible adsorption and desorption of electrolyte ions on electrode surfaces [5,35,36]. They offer high power density, fast charge/discharge rates, and a long cycle life. However, their energy density is limited by the low capacitance of conventional electrode materials. To overcome this limitation, CNTs have been widely used as electrode materials or additives in supercapacitors, owing to their high surface area, electrical conductivity, and mechanical strength (Figure 4) [5,35–37]. However, the dispersion state of CNTs within the electrode

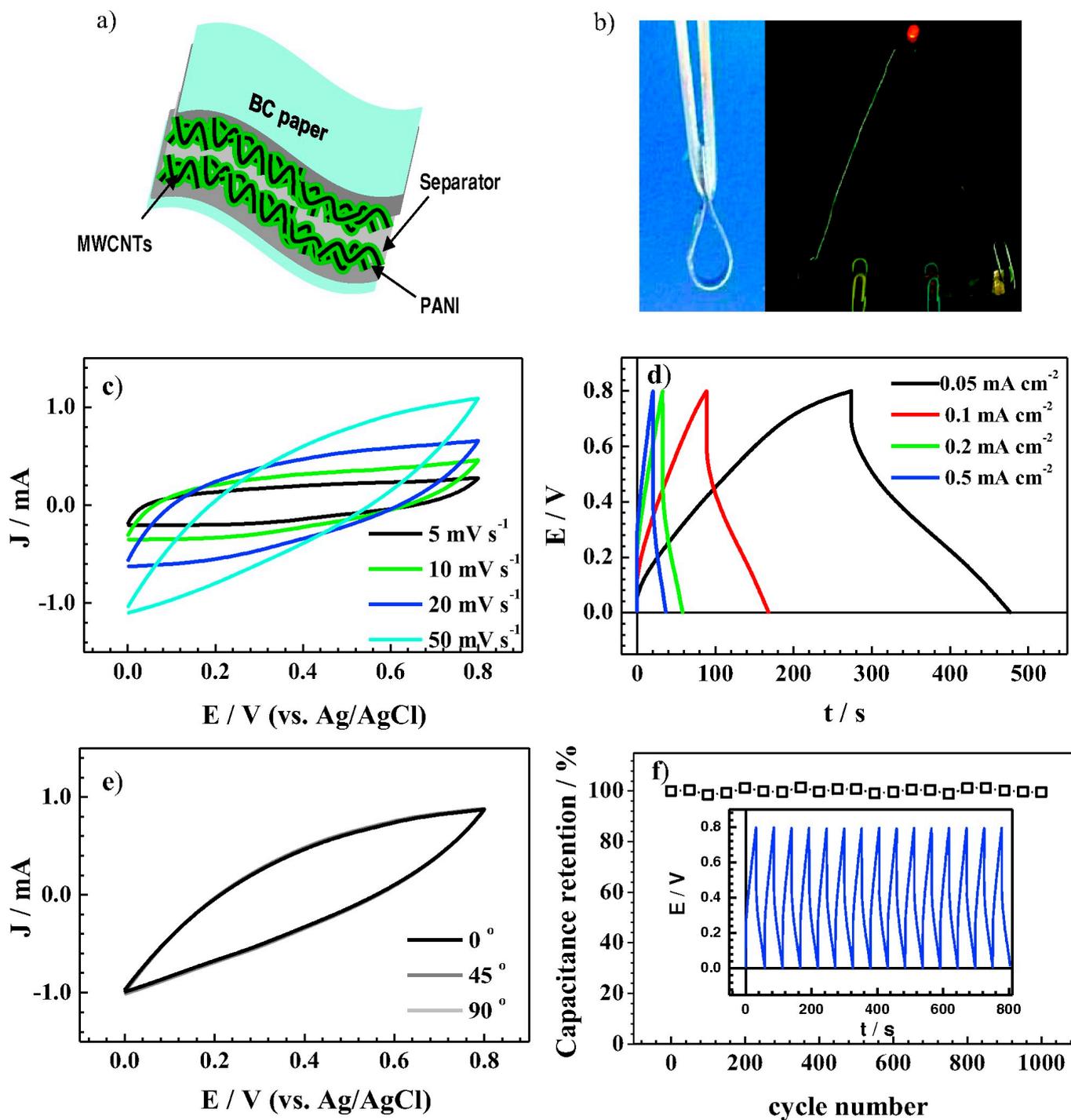
matrix has a significant impact on their electrochemical performance. In this subsection, we will discuss how CNT dispersion stability influences three key factors that determine the capacitance of supercapacitor electrodes: electrode surface area and accessibility, ion diffusion kinetics, and charge storage capacity.



**Figure 4.** Types of CNT electrodes for producing flexible supercapacitors [37]. Reproduced from ref. [37] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License.

The capacitance of a supercapacitor electrode is proportional to its accessible surface area for electrolyte ion adsorption [38–40]. Therefore, maximizing the surface area and accessibility of CNTs within the electrode matrix is crucial for enhancing the capacitance. This can be achieved by ensuring the uniform dispersion of CNTs within the electrode matrix, avoiding agglomeration and entanglement that reduce the effective surface area and block the access of ions to nanotube surfaces. Well-dispersed CNTs engineer a microstructure replete with numerous nanotube–electrolyte contact points [38–40]. This intricate framework translates into a remarkably elevated accessible surface area, enabling an intensified interaction between the electrode material and the electrolyte ions. Consequently, the capacitance of the electrode escalates, laying the foundation for heightened energy storage capabilities. For example, Li et al. fabricated supercapacitor electrodes using well-dispersed MWCNTs with polyaniline (PANI) and bacterial cellulose (BC) [28]. The MWCNTs acted as a conductive scaffold for PANI deposition and provided a large surface area for ion adsorption. The well-dispersed MWCNTs also enhanced the contact between PANI and the electrolyte, improving the utilization efficiency of PANI. The MWCNT/PANI composite electrodes exhibited a high specific capacitance of 656 F/g at a current density of 10 A/g (Figure 5) [28].

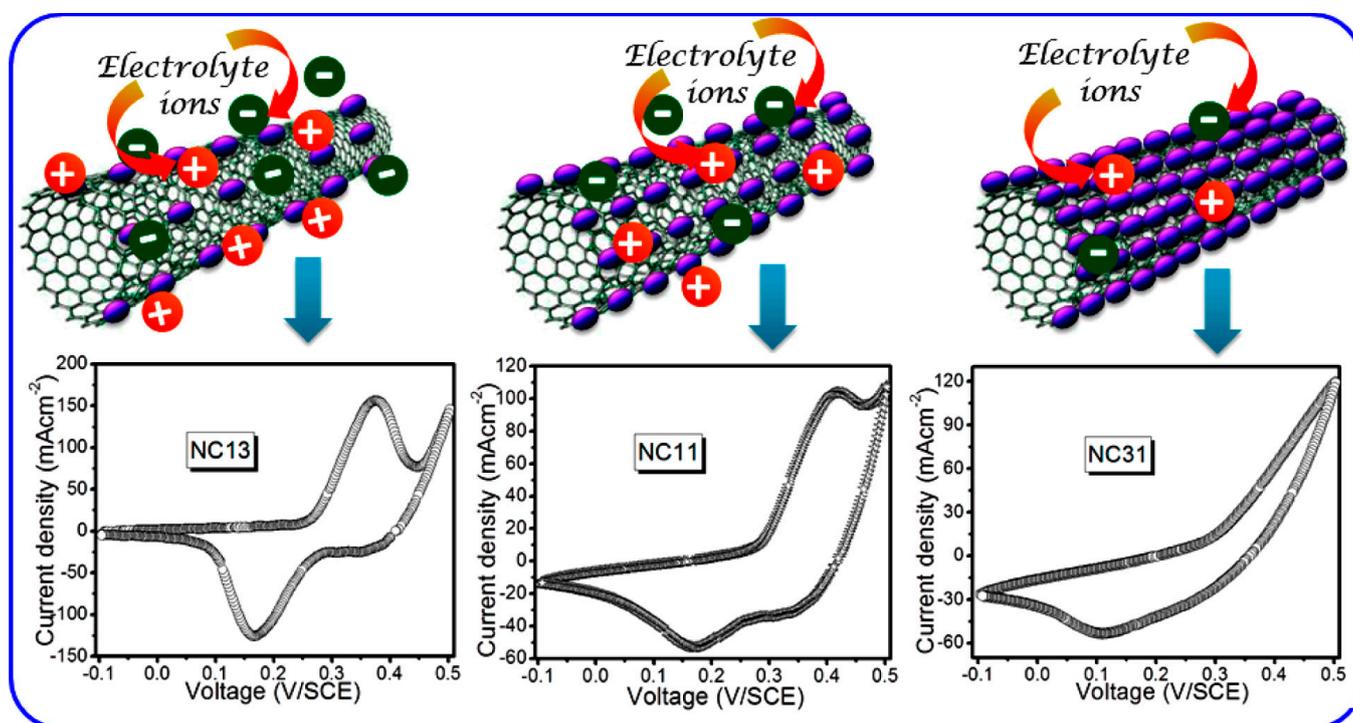
The rate performance of a supercapacitor electrode depends on how fast the electrolyte ions can diffuse within the electrode matrix and reach the active sites for adsorption/desorption [38–40]. Therefore, optimizing the ion diffusion kinetics within the electrode matrix is essential for achieving fast charge/discharge cycles. This can be influenced by the dispersion state of CNTs within the electrode matrix, which determines the porosity and tortuosity of the electrode structure [38–40]. Uniform dispersion establishes an interconnected network of nanotubes, akin to a well-organized transport system. Ions navigate this network seamlessly, encountering minimal resistance and enabling swift charge/discharge kinetics. In contrast, agglomerates disrupt this coherent pathway, impeding ion diffusion and resulting in sluggish performance. For example, SWCNTs functionalized with sulfonic acid groups ( $-\text{SO}_3\text{H}$ ) showed an excellent dispersibility [29]. The  $-\text{SO}_3\text{H}$  groups enhanced the dispersion stability of SWCNTs in water and increased their affinity with aqueous electrolytes. The well-dispersed SWCNTs formed a porous network structure with large pore volume and low tortuosity, facilitating ion diffusion within the electrode matrix.



**Figure 5.** (a) A schematic structure of a solid-state supercapacitor device. (b) The optical images of a flexible supercapacitor device based on BC-MWCNTs-PANI<sub>10</sub> (left) and a red LED lighted by such devices (right). (c) Capacitance/voltage (CV) curves at different scan rates, (d) galvanostatic charging/discharging curves at different discharge rates, and (e) CV scans at different curvature for solid-state devices based on BC-MWCNTs-PANI<sub>10</sub> electrode. (f) Cycling stability of solid-state device over 1000 cycles. The inset shows the galvanostatic charge/discharge curves [28]. Reproduced with permission from ref. [28]. Copyright 2014 Wiley.

The energy density of a supercapacitor electrode is determined by its charge storage capacity, which is related to the number and availability of sites for electrolyte ion adsorption [38–40]. Therefore, increasing the charge storage capacity of CNTs within the

electrode matrix is vital for enhancing the energy density. This can be controlled by the dispersion state of CNTs within the electrode matrix, which affects the surface chemistry and morphology of nanotubes. Well-dispersed CNTs create a densely populated array of sites, elevating the overall charge storage capacity of the electrode. This not only enhances the energy storage potential, but also prolongs the operational life of the supercapacitor, as the mitigated agglomeration-induced degradation ensures sustained performance. For example, MWCNTs decorated with nickel oxide (NiO) nanoparticles displayed an excellent dispersion states in water [41]. The NiO nanoparticles were uniformly distributed on the surface of MWCNTs using a hydrothermal method, forming a core-shell structure. The well-dispersed MWCNTs provided a large surface area and a conductive backbone for NiO deposition and charge transport. The NiO nanoparticles contributed to the pseudocapacitance of the electrode by providing additional sites for redox reactions with electrolyte ions. The MWCNT/NiO composite electrodes exhibited a high specific capacitance of 1727 F/g at a current density of 5 mA/cm<sup>2</sup> (Figure 6) [41].

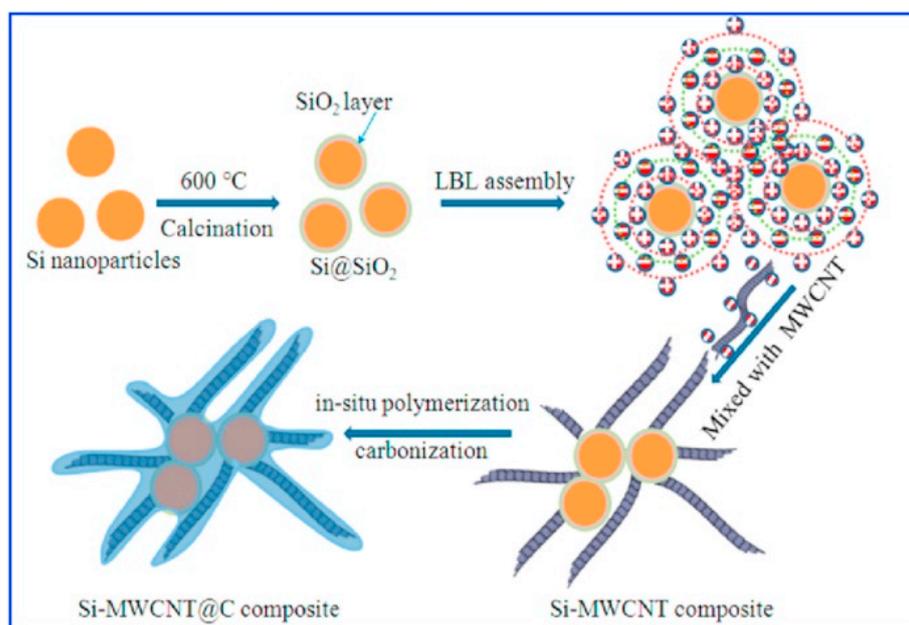


**Figure 6.** Schematic representation of impact of mass loading effect on the intercalation/deintercalation of ions and, subsequently, on CV curves [41]. Reproduced with permission from ref. [41]. Copyright 2014 American Chemical Society.

#### 4.2. Batteries

Batteries are electrochemical devices that store and release energy through reversible redox reactions between electrode materials and electrolyte ions [42–46]. They offer high energy density, a long cycle life, and environmental friendliness. However, their power density and durability are limited by the poor conductivity and mechanical stability of conventional electrode materials [42–45]. To overcome these limitations, CNTs have been widely used as electrode materials or additives in batteries, owing to their high conductivity, mechanical strength, and compatibility with various active materials [42–45]. However, the dispersion state of CNTs within the electrode matrix has a significant impact on their electrochemical performance. In this subsection, we will discuss how CNT dispersion stability influences three key factors that determine the performance of battery electrodes: mechanical stability, electron transport, and energy density. We will also provide some examples of CNT-based electrodes that demonstrate the benefits of dispersion stability in batteries.

As the energy landscape pivots toward sustainable solutions, batteries emerge as focal points for innovation. The dispersion state of CNTs within battery electrodes plays a crucial role in maintaining their structural integrity. During charge/discharge cycles, electrode materials undergo volume changes due to the intercalation/deintercalation of electrolyte ions [42–45,47]. These volume changes induce mechanical stress within the electrode matrix, leading to the cracking and pulverization of active materials and loss of contact with current collectors [42–45,47]. Agglomerates, acting as stress concentrators, exacerbate mechanical strain during charge/discharge cycles. On the other hand, well-dispersed CNTs distribute stress uniformly, curbing mechanical degradation and extending the lifespan of the electrode [42–45,47]. This resilience to mechanical stress translates to enhanced battery durability, a factor paramount in energy storage applications. For example, Zhang et al. fabricated lithium-ion battery electrodes using well-dispersed MWCNTs coated with silicon (Si) nanoparticles (Figure 7) [30]. The Si nanoparticles were uniformly dispersed on the surface of MWCNTs using a sol-gel method, forming a core-shell structure. The well-dispersed MWCNTs acted as a buffer layer to accommodate the large volume expansion of Si during lithiation/delithiation cycles. The MWCNT/Si composite electrodes showed excellent cycle stability, showing 937 mAh/g over 450 cycles [30]. In addition, surface functionalization of carbon nanotubes holds a specific significance in Li-S batteries, as it plays a pivotal role in shaping battery performance and ensuring long-term stability [48–51]. For example, Dorfler et al. conducted functionalization of CNTs with sulfur (S), resulting in a notably high capacity of 800 mAh/g [48]. In the work by Ma et al., the authors enveloped CNTs with a polyethylenimine (PEI) polymer, significantly enhancing dispersibility and leading to a remarkable capacity of 838 mAh/g [51]. Liang et al. chose to functionalize CNTs with oxygen, resulting in a capacity of 798.5 mAh/g [50]. Finally, Kim et al. performed functionalization of CNTs through oxygen thermal treatment, achieving an impressive capacity of 1239.8 mAh/g [49].



**Figure 7.** Schematic of the fabrication of Si-MWCNT@C composite [30]. Reproduced with permission from ref. [30]. Copyright 2016 Elsevier.

In the intricate dance of charge and discharge processes within batteries, electron transport takes center stage [42–45,47]. The rate performance and efficiency of battery electrodes depend on how fast electrons can transfer between active materials and current collectors [42–45,47]. Therefore, enhancing the electron transport within the electrode matrix is essential for optimizing charge/discharge efficiency and minimizing energy loss [42–45,47].

This can be influenced by the dispersion state of CNTs within the electrode matrix, which determines the electrical conductivity and percolation threshold of the electrode structure. Uniform dispersion of CNTs within the electrode matrix establishes an interconnected network that facilitates efficient electron transfer [42–45,47,52,53]. This unobstructed pathway for electrons reduces internal resistance, optimizing charge/discharge efficiency. The result is a battery that not only stores and releases energy effectively but does so with minimal energy loss.

The summary of energy storage performance using CNTs functionalized with various method is presented in Table 2. The dispersion stability of CNTs sets the stage for the overall energy density of batteries, a critical metric in energy storage. Agglomerates introduce inconsistencies in charge distribution, leading to non-uniform energy storage and reduced capacity utilization. Conversely, well-dispersed CNTs facilitate uniform energy distribution, enhancing energy density and capacity utilization. Moreover, the preservation of electrode integrity achieved through dispersion stability culminates in enhanced cycle stability. The ability of the electrode to endure prolonged charge/discharge cycles with minimal capacity fade positions the battery for long-term and reliable operation.

**Table 2.** Summary of energy storage performance using CNTs functionalized using various methods.

Application Type	Functionalization Method	Materials	Ref.
Supercapacitor	PANI-MWCNT/BC	656 F/g at 10 A/g	[28]
	MWCNTs with NiO NPs	1727 F/g at 5 mA/cm <sup>2</sup>	[41]
	SWCNTs functionalized with sulfonic acid groups	1183 at 5 A/g	[29]
Battery	MWCNTs coated with Si NPs	937 mAh/g	[30]
	CNT-S functionalization	800 mAh/g	[48]
	CNT- polyethylenimine (PEI)	838 mAh/g	[51]
	CNT-oxygen functionalization	798.5 mAh/g	[50]
	Oxygen treatment of CNT	1239.8 mAh/g	[49]

## 5. Future Trajectories and Navigating Challenges

The quest for optimizing CNT dispersion stability is an ongoing journey that reveals a spectrum of challenges and opportunities. The advancement of this field opens up new avenues for exploring the full potential of CNTs for energy storage and harvesting applications. In this section, we survey the landscape of future directions, highlighting the obstacles to be surmounted and the prospects that await. A key prerequisite for achieving optimal CNT dispersion stability is the accurate characterization of dispersion states [17,18]. This calls for the development of advanced analytical techniques that can provide a comprehensive understanding of dispersion dynamics. These techniques include state-of-the-art microscopy methods that can visualize nanoscale features and spectroscopic techniques that can probe intermolecular interactions. The integration of these techniques can reveal valuable insights into the mechanisms and factors that govern dispersion behavior. Another important aspect of CNT dispersion stability is its temporal evolution. Real-time monitoring techniques, capable of detecting changes in dispersion over time, are essential for elucidating the kinetics of agglomeration and stabilization processes [17,18]. These techniques can also enable dynamic feedback loops, allowing for the adjustment of stability strategies in situ.

A promising strategy for improving CNT dispersion stability is the tailoring of CNT surfaces with precision and purpose [2,6,12,16,20,25,27,31–33,36,43,47]. This involves the application of advanced functionalization strategies, driven by the synergy of chemistry and materials science, that can create surfaces that interact favorably with various matrices. These strategies include covalent and non-covalent approaches, guided by molecular engineering, that can introduce functional groups that enhance both stability and compatibility.

Another innovative strategy for enhancing CNT dispersion stability is the incorporation of smart additives and the design of hybrid architectures [14,16,17,22,39,44,47]. These include novel dispersants and surface modifiers, endowed with responsive functionalities, that can modulate stability dynamically. They also include the integration of CNTs within polymer matrices, carefully designed to optimize dispersion, that can result in new materials that combine the advantages of both components.

The field of CNT dispersion stability is an evolving journey that presents a range of challenges and opportunities. Advanced analytical techniques, along with real-time monitoring, will reveal the details of dispersion dynamics. Ingenious strategies, such as tailored surface engineering and smart additives, will overcome the difficulties of enhancing stability. Collaborations among disciplines will integrate expertise, unleashing the potential of CNTs for energy storage and harvesting applications. The radiant future of CNT dispersion stability is one where the combination of scientific creativity, collaborative spirit, and continuous innovation leads to a new era of energy technologies. As current challenges inspire future advancements, the exploration of CNT dispersion stability will demonstrate the transformative power of multidisciplinary research, guiding us towards sustainable and efficient energy solutions that surpass the limits of possibility.

## 6. Conclusions

This review paper highlights the importance of CNT dispersion stability as a key factor that influences the performance of energy storage and harvesting devices. Dispersion stability is essential for maintaining and enhancing the intrinsic properties of CNTs, such as high surface area, electrical conductivity, and mechanical strength, that make them attractive for energy applications. Dispersion stability also enables the effective integration of CNTs within device architectures, facilitating the optimization of energy conversion processes, such as light absorption, charge separation and transport, and recombination suppression. Dispersion stability thus bridges the gap between theoretical potential and practical application, demonstrating its indispensability in harnessing the nanoscale advantages of CNTs for energy technologies. Achieving dispersion stability requires overcoming the challenges posed by agglomeration, which degrades the performance and stability of CNTs. This calls for the development of multidisciplinary solutions that involve surface functionalization, surfactant mediation, and novel matrix integration, which can tailor the interactions between CNTs and their surrounding media. These solutions not only improve dispersion stability, but also create new opportunities for designing innovative materials and structures that combine the benefits of CNTs and other components. This synergy of scientific investigation and real-world implementation showcases dispersion stability's transformative potential. As we explore the intersection of science and engineering, we envision an era in which dispersion stability evolves from a theoretical concept to a practical necessity, driving energy technologies towards new levels of efficiency and sustainability. This journey, a tribute to human innovation and perseverance, inspires the future, where energy storage and harvesting reach new heights of possibility, resonating with the harmony of scientific excellence, engineering skill, and the aspiration for a sustainable energy landscape.

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