ISSN PRINT 2319 1775 Online 2320 7876

  UGC CARE Listed (Group -I) Journal Volume 11, Iss 6, June 2022

Review of Polymer-Grafted Carbon Nanotubes: Synthesis, Properties, and Applications

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Abstract

This review examines the synthesis, properties, and diverse applications of polymer-grafted carbon nanotubes (CNTs). Polymer grafting onto CNTs represents a significant advancement in nanomaterial science, enhancing the functional versatility and applicability of CNTs in various fields. The synthesis methods discussed encompass both covalent and non-covalent approaches, highlighting their respective advantages in achieving tailored polymer-CNT hybrids with controlled structures and properties. The properties of polymer-grafted CNTs, including mechanical strength, electrical conductivity, and thermal stability, are critically analyzed in the context of their application potential. The synergistic combination of CNTs' intrinsic properties with the functional attributes imparted by polymers broadens their utility in fields such as nanocomposites, sensors, biomedical devices, and energy storage systems. Key applications reviewed include the use of polymer-grafted CNTs in enhancing mechanical properties and electrical conductivity of composites, improving sensitivity and selectivity in sensor devices, enabling controlled drug delivery in biomedical applications, and enhancing performance in energy storage devices. this review underscores the transformative impact of polymer grafting on CNTs, offering insights into current advancements, challenges, and future directions in utilizing these hybrid materials across various technological domains.

Introduction

Carbon nanotubes (CNTs) have garnered immense interest in the realm of nanotechnology due to their exceptional mechanical, electrical, and thermal properties. These properties make CNTs promising candidates for numerous applications ranging from nanocomposites to biomedical devices and energy storage systems. However, the integration of CNTs into practical applications often requires enhancing their dispersion, stability, and compatibility with other materials, which can be achieved through surface modification techniques such as

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polymer grafting. Polymer grafting onto CNTs involves covalently or non-covalently attaching polymer chains onto the nanotube surface. This process not only enhances the dispersibility and solubility of CNTs in various solvents and matrices but also introduces new functionalities and properties to the nanotubes. The choice of polymer and grafting method is crucial as it determines the overall characteristics and performance of the polymer-grafted CNTs in specific applications.

In recent years, significant research efforts have been directed towards synthesizing and characterizing polymer-grafted CNTs to exploit their full potential in diverse applications. Covalent functionalization methods involve chemical reactions that modify the surface of CNTs with polymer chains, offering precise control over the grafting density and orientation. Non-covalent approaches, on the other hand, utilize physical interactions such as π-π stacking, hydrogen bonding, or electrostatic interactions to attach polymers onto CNT surfaces, preserving the intrinsic properties of both materials. The properties of polymer-grafted CNTs are tailored according to the specific application requirements. For instance, in nanocomposites, polymer grafting enhances the interfacial adhesion between CNTs and the polymer matrix, thereby improving mechanical strength, electrical conductivity, and thermal stability of the composite materials. In biomedical applications, polymer-grafted CNTs facilitate targeted drug delivery systems, biosensors, and imaging agents due to their biocompatibility and functionalizability. This paper aims to provide a comprehensive overview of the synthesis methods, properties, and applications of polymer-grafted CNTs. By synthesizing existing literature and highlighting recent advancements, this review seeks to elucidate the transformative potential of polymer-grafted CNTs in advancing nanotechnology and addressing contemporary challenges in various industrial sectors.

Need of the Study

The study on the synthesis and characterization of polymer-grafted carbon nanoparticles is essential due to its potential to revolutionize several key industries and address pressing technological challenges. Carbon nanoparticles, such as carbon nanotubes (CNTs) and carbon nanofibers (CNFs), exhibit exceptional mechanical strength, electrical conductivity, and large surface area, making them highly desirable for applications in aerospace, automotive, electronics, biomedical, and environmental sectors. the development of polymer-grafted carbon nanoparticles offers enhanced mechanical and thermal properties, crucial for lightweight and high-strength composite materials in aerospace and automotive industries. By functionalizing the carbon nanoparticle surface with polymers through innovative synthesis techniques like atom transfer radical polymerization (ATRP), researchers can tailor these materials to specific application needs, such as improving structural integrity and durability. characterization of these nanocomposites is vital for understanding their structural integrity, dispersion within matrices, and chemical interactions at the nanoscale. Techniques like scanning electron microscopy (SEM), transmission electron microscopy (TEM), and spectroscopic analyses (FTIR, Raman) provide insights into morphology, distribution, and bonding states, crucial for optimizing material performance and reliability.

the study addresses environmental and biomedical challenges by exploring applications such as water purification, biomedical sensors, and drug delivery systems. These applications benefit from the unique properties and functionalization capabilities of polymer-grafted carbon nanoparticles, offering sustainable solutions and advancements in healthcare technology. In essence, the study on polymer-grafted carbon nanoparticles bridges fundamental research with practical applications, driving innovation across industries and contributing to the development of next-generation materials with enhanced functionalities and performance

Significance of the Study

The significance of studying the synthesis and characterization of polymer-grafted carbon nanoparticles lies in its potential to innovate across various technological domains and address critical challenges in industry and research. These nanoparticles, including carbon nanotubes (CNTs) and carbon nanofibers (CNFs), possess exceptional properties such as high mechanical strength, electrical conductivity, and surface area-to-volume ratio, making them promising candidates for numerous applications.

Advancements in synthesizing polymer-grafted carbon nanoparticles offer opportunities to develop lightweight, high-strength composite materials. These materials can revolutionize aerospace and automotive industries by enhancing structural integrity and fuel efficiency, thereby contributing to sustainable transportation solutions. the characterization of these nanocomposites is crucial for understanding their physical and chemical properties. Techniques like electron microscopy (SEM, TEM) and spectroscopic methods (FTIR, Raman) provide insights into nanoparticle morphology, dispersion within matrices, and chemical interactions. This knowledge facilitates the optimization of material design and performance in diverse applications. Polymer-grafted carbon nanoparticles can be tailored for applications in water purification, where their adsorption properties and durability offer efficient solutions for removing contaminants from water sources. In biomedical fields, these nanoparticles enable advancements in drug delivery systems and medical imaging, leveraging their biocompatibility

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and functionalization capabilities for targeted therapies and diagnostics. research into polymer-grafted carbon nanoparticles bridges fundamental science with practical applications, driving innovation across industries and contributing to sustainable development goals. The study's findings have the potential to pave the way for new technologies, materials, and solutions that enhance efficiency, sustainability, and quality of life globally.

Literature Review

Basheer, B. V., George, et al (2020). Polymer-grafted carbon nanotubes (CNTs) represent a significant advancement in nanotechnology, combining the unique properties of CNTs with the versatility of polymers. The synthesis of these hybrid materials involves covalently attaching polymer chains onto the CNT surface through various methods such as radical polymerization, click chemistry, or grafting from approaches using initiators. This allows precise control over polymer chain length, density, and composition, tailoring the material's properties to specific applications. The properties of polymer-grafted CNTs are enhanced compared to pristine CNTs or polymers alone. They exhibit improved dispersibility in solvents and matrices, which enhances their processability and allows for uniform dispersion in polymer matrices. This dispersion leads to enhanced mechanical, electrical, thermal, and barrier properties in composite materials. The polymer chains also provide functional groups that can further modify surface properties or facilitate interactions with other materials. Applications of polymer-grafted CNTs span various fields including aerospace, electronics, biomedical devices, and energy storage. In aerospace, they contribute to lightweight, strong composites for structural applications. In electronics, their improved electrical conductivity and thermal management properties enable advancements in conductive films, sensors, and electromagnetic interference shielding. In biomedical fields, their biocompatibility and functionalization potential support applications such as drug delivery systems and biosensors. Moreover, in energy storage, they enhance the performance of electrodes in batteries and supercapacitors. polymer-grafted CNTs represent a promising class of nanocomposites with tailored properties that address specific challenges across diverse industries, driving innovation in materials science and technology.

Yang, Q., Wang, L., et al (2007). The preparation of polymer-grafted carbon black nanoparticles using surface-initiated atom transfer radical polymerization (SI-ATRP) involves a controlled method to attach polymer chains onto the surface of carbon black particles. In SI-

ISSN PRINT 2319 1775 Online 2320 7876
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ATRP, the process begins with functionalizing the surface of carbon black nanoparticles with initiator molecules capable of initiating polymerization. These initiators are typically anchored onto the surface through covalent bonds, ensuring they remain active during subsequent polymerization steps. Once anchored, the nanoparticles are introduced into a reaction mixture containing monomers, a catalyst complex (typically based on copper), and a reducing agent. The ATRP process then proceeds in a controlled manner: the initiator on the nanoparticle surface activates the monomer, allowing polymer chains to grow from the surface of each nanoparticle. Importantly, this controlled polymerization technique enables precise control over polymer chain length, composition, and dispersity. It ensures that polymer grafts are uniform and well-defined, which is crucial for achieving desired material properties. The resulting polymer-grafted carbon black nanoparticles exhibit enhanced properties compared to pristine carbon black. These properties include improved dispersion in polymer matrices, enhanced mechanical strength, modified surface properties, and tailored functionalities based on the nature of the grafted polymer. Such materials find applications in areas ranging from advanced composites and coatings to biomedical devices and energy storage, where their unique combination of properties can be exploited for specific functional requirements.

Mu, Q., Yang, L., Davis, et al (2010). The biocompatibility of polymer-grafted core/shell iron/carbon nanoparticles is pivotal for their integration into biomedical applications. These nanoparticles typically feature an iron core enveloped by a carbon shell, onto which polymer chains are grafted through various techniques. This surface modification plays a crucial role in enhancing biocompatibility by shielding the iron core, thereby minimizing potential cytotoxicity and improving stability in biological environments. The polymer coating not only serves as a protective barrier against the release of toxic ions but also allows for surface functionalization with biomolecules, enabling targeted interactions with cells or tissues. Biocompatibility assessments involve rigorous in vitro studies to evaluate cellular responses such as cytotoxicity, cellular uptake, and compatibility with biological fluids. Furthermore, in vivo studies assess systemic toxicity, biodistribution, and long-term effects within living organisms. These nanoparticles hold promise for applications in targeted drug delivery, imaging diagnostics, and therapeutic interventions, where their biocompatible nature is essential for ensuring safety and efficacy in clinical settings.

Li, X., Hong, C. Y., et al (2010). The preparation and characterization of hyperbranched polymer grafted mesoporous silica nanoparticles via self-condensing atom transfer radical vinyl polymerization (SCATRP-V) is a sophisticated method aimed at enhancing the

ISSN PRINT 2319 1775 Online 2320 7876
  UGC CARE Listed (Group -I) Journal Volume 11, Iss 6, June 2022

functionality and versatility of silica nanoparticles for various applications. This process begins with the modification of mesoporous silica nanoparticles using surface-initiated atom transfer radical polymerization (ATRP), where specific initiators are anchored onto the silica surface. These initiators facilitate the controlled polymerization of vinyl monomers, leading to the growth of hyperbranched polymers directly from the nanoparticle surface. The resulting hyperbranched structure offers several advantages, including increased surface area coverage, enhanced loading capacity, and improved compatibility with different matrices. Characterization of these nanoparticles involves advanced techniques such as TEM and SEM for morphological analysis, FTIR for chemical bonding confirmation, and BET analysis to assess surface area and pore structure. Applications of hyperbranched polymer grafted mesoporous silica nanoparticles span fields like drug delivery, catalysis, sensing, and biomedical imaging, leveraging their tailored properties to achieve targeted and efficient performance in complex environments. This approach exemplifies a strategic integration of polymer chemistry and nanotechnology to develop next-generation materials with precise control over structure and functionality.

Baskaran, D., Mays, J. W., et al (2014). Polymer-grafted multiwalled carbon nanotubes (MWCNTs) synthesized via surface-initiated polymerization represent a significant advancement in nanomaterial engineering, combining the exceptional properties of MWCNTs with the versatility of polymers. The process begins by functionalizing the surface of MWCNTs with suitable initiators that can initiate polymerization. Common initiators include diazonium salts or silane coupling agents, which form stable bonds with the nanotube surface. These initiators enable the controlled growth of polymer chains from the nanotube surface, typically through techniques like atom transfer radical polymerization (ATRP) or controlled radical polymerization (CRP). The polymer grafting process imparts several advantageous properties to the MWCNTs. Firstly, it improves the dispersibility of MWCNTs in various solvents and polymer matrices, facilitating their uniform incorporation into composite materials. This enhanced dispersibility contributes to improved mechanical, electrical, and thermal properties of the composites. Secondly, the grafted polymer chains provide functional groups that can further modify the surface chemistry of MWCNTs, enhancing compatibility with other materials and enabling specific functionalities such as bioconjugation or sensing capabilities. Characterization techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and thermogravimetric analysis (TGA) are employed to assess the morphology, chemical composition, and thermal stability of the polymer-grafted MWCNTs. These analyses confirm the successful grafting of polymer chains onto the nanotube surface and provide insights into their structure-property relationships. Applications of polymer-grafted MWCNTs span a wide range of fields including aerospace, electronics, biomedical devices, and environmental remediation. They are utilized in developing advanced materials for lightweight composites, conductive films, sensors, drug delivery systems, and water purification technologies. Overall, polymer-grafted MWCNTs exemplify the synergy between nanotechnology and polymer chemistry, offering tailored solutions for complex engineering challenges in various industrial and scientific domains.

Tsubokawa, N. (2015). The preparation and characterization of polymer-grafted carbon nanotubes (CNTs) and nanofibers involve sophisticated methods aimed at enhancing their structural and functional properties for diverse applications. Initially, the surface of CNTs or nanofibers is functionalized with appropriate initiators that facilitate polymerization directly onto their surfaces. This process can utilize techniques such as atom transfer radical polymerization (ATRP), grafting from methods, or click chemistry, ensuring controlled growth and uniform coverage of polymer chains. Polymer grafting significantly alters the properties of CNTs and nanofibers. It improves their dispersibility in solvents and matrices, facilitating easier incorporation into composite materials. This enhanced dispersibility contributes to improved mechanical reinforcement, electrical conductivity, and thermal stability of the resulting nanocomposites. Moreover, the grafted polymers introduce functional groups that modify surface properties, enabling tailored interactions with other materials or biological entities. Characterization techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FTIR), and Raman spectroscopy are employed to analyze the morphology, structure, and chemical composition of polymer-grafted CNTs and nanofibers. These techniques confirm the successful attachment of polymer chains and provide insights into their distribution and orientation on the nanomaterial surface. Applications of polymer-grafted CNTs and nanofibers span various fields including aerospace, automotive, electronics, biomedical devices, and environmental remediation. They are utilized in developing high-performance composite materials, conductive coatings, sensors, drug delivery systems, and filtration membranes. Their unique combination of properties makes them indispensable for advancing technology in fields requiring lightweight, durable, and functional materials. In conclusion, the preparation and characterization of polymer-grafted carbon nanotubes and nanofibers exemplify a tailored

ISSN PRINT 2319 1775 Online 2320 7876
  UGC CARE Listed (Group -I) Journal Volume 11, Iss 6, June 2022

approach to harnessing nanomaterials' potential through precise surface modification, offering solutions to complex challenges across industries and scientific disciplines.

Research Problem

The research problem involves synthesizing and characterizing polymer-grafted carbon nanoparticles. This area of study is crucial due to the increasing demand for advanced materials with enhanced properties for various applications such as biomedical, environmental remediation, and industrial processes. Polymer-grafted carbon nanoparticles combine the unique properties of both polymers and carbon nanoparticles, offering advantages such as improved stability, dispersibility, and functionality compared to their individual components.

The synthesis process typically involves the functionalization of carbon nanoparticles with polymer chains through various chemical or physical methods, aiming to achieve a controlled grafting density and polymer chain length. Characterization plays a pivotal role in assessing the structural integrity, morphology, thermal stability, and surface chemistry of these hybrid materials. Techniques such as spectroscopy (FTIR, Raman), microscopy (SEM, TEM), thermal analysis (TGA, DSC), and surface analysis (XPS) are commonly employed to comprehensively analyze their properties.

Addressing this research problem involves optimizing synthesis conditions to achieve tailored material properties and understanding the structure-property relationships that govern their performance. Furthermore, exploring the potential applications of polymer-grafted carbon nanoparticles in diverse fields underscores the practical significance of this research endeavor, contributing to advancements in material science and technology.

IJFANS INTERNATIONAL JOURNAL OF FOOD AND NUTRITIONAL SCIENCES
ISSN PRINT 2319 1775 Online 2320 7876
Research paper UGC CARE Listed (Group -I) Journal Volume 11, Iss 6, June 2022

Scope of the Research

The scope of this research encompasses several key aspects related to the synthesis and characterization of polymer-grafted carbon nanoparticles. Primarily, the study will focus on exploring different methods for grafting polymers onto carbon nanoparticles, aiming to achieve optimal grafting efficiency and control over polymer chain length and density. This includes investigating chemical and physical techniques such as radical polymerization, surface-initiated polymerization, and click chemistry, among others, to tailor the properties of the resulting hybrid materials.

Characterization forms another critical component of the scope, involving the use of advanced analytical techniques to assess the structural, morphological, thermal, and surface properties of polymer-grafted carbon nanoparticles. Techniques such as Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM), thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and X-ray photoelectron spectroscopy (XPS) will be employed. These analyses will provide insights into the composition, dispersion, stability, and functional groups present on the nanoparticle surfaces. performance and potential applications of these hybrid materials in practical settings. This includes assessing their suitability for biomedical applications such as drug delivery systems, environmental applications like water purification and pollutant remediation, and industrial uses such as catalyst supports and energy storage devices. the research aims to advance the understanding of polymer-grafted carbon nanoparticles and their diverse applications, contributing to the development of novel materials with enhanced properties and functionalities for various technological and industrial purposes.

Conclusion

The review of polymer-grafted carbon nanotubes (CNTs) underscores their significant role in advancing nanomaterial science and expanding the application horizons of CNTs. Synthesis methods, including covalent and non-covalent approaches, have been pivotal in tailoring the properties of polymer-grafted CNTs to meet diverse technological demands. Covalent functionalization offers precise control over grafting density and orientation, while non-covalent methods preserve the intrinsic properties of CNTs, enhancing their compatibility with various matrices. The properties of polymer-grafted CNTs, such as improved dispersibility, mechanical reinforcement, electrical conductivity, and biocompatibility, have enabled their deployment in numerous fields. In nanocomposites, these hybrid materials enhance the structural integrity and functional performance by serving as reinforcing agents and conductive fillers. In biomedical applications, polymer-grafted CNTs show promise in drug delivery, biosensing, and imaging technologies, capitalizing on their unique surface chemistry and biological interactions. Ongoing research efforts focus on optimizing synthesis techniques to further enhance the performance and scalability of polymer-grafted CNTs. Challenges such as achieving uniform dispersion, scalability of production, and ensuring long-term stability in complex environments continue to drive innovation in this field. Polymer grafting represents a versatile strategy to harness the intrinsic properties of CNTs while imparting tailored functionalities for specific applications. As interdisciplinary collaborations and technological advancements accelerate, polymer-grafted CNTs are poised to play an increasingly pivotal role in revolutionizing materials science and addressing multifaceted challenges across various industrial sectors.

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