Asian Journal of Applied Science and Technology (AJAST)
Volume 7, Issue 3, Pages 16-27, July-September 2023

Advancements and Prospects of Composites Consisting of Carbon-Nanomaterial-Dispersed Liquid Crystals

Ankesh Kumar[1*], Ankita Mathur[2] & Dr. Preeti Singh Bahadur[3]

*[1]Assistant Professor, Department of Physics, Amity University, Greater Noida, India. [2]Assistant Professor, Department of Chemistry, Amity University, Greater Noida, India. [3]Associate Professor, Department of Physics, Amity University, Greater Noida, India. Corresponding Author (Ankesh Kumar) Email: akumar5@gn.amity.edu**

DOI: https://doi.org/10.38177/ajast.2023.7302

Article Received: 15 May 2023 *Article Accepted: 05 July 2023* *Article Published: 14 July 2023*

ABSTRACT

This research paper presents a thorough examination of the progress and potential of composites that consist of carbon nanomaterials dispersed in liquid crystals. These composites have attracted considerable interest in recent years due to their unique combination of properties and their wide range of applications. Specifically, this paper focuses on the incorporation of carbon nanotubes (CNTs) and graphene into liquid crystal matrices. The synthesis methods utilized for the preparation of these composites, including dispersion techniques and alignment strategies, are discussed in detail. Moreover, the paper investigates the effects of incorporating carbon nanomaterials on the structural, electrical, and optical properties of liquid crystals. The potential applications of these composites in various fields such as optoelectronic devices, sensors, and energy storage systems are also explored. Furthermore, significant attention is given to recent experimental findings and theoretical studies, which demonstrate the remarkable advancements achieved in the performance of these composites. Moreover, the research delves into forthcoming opportunities and obstacles in the domain while emphasizing scalability, stability, and device integration. Collectively, this scholarly article sheds light on the progress and possibilities of composites that encompass carbon-nanomaterial-dispersed liquid crystals, thus underscoring their prospective role in emerging technologies.

Keywords: Carbon nanotubes; Graphene; Liquid crystal composites; Nanocomposites; Nanotechnology; Structural materials; Electrical properties; Mechanical properties; Optical properties; Manufacturing techniques.

1. Introduction

1.1. Background

Composites comprising of carbon nanomaterials dispersed within liquid crystal matrices have gained significant traction in recent years, primarily due to their remarkable combination of properties and potential applicability. Liquid crystals, distinguished by their ordered molecular arrangements and intermediate state between solids and liquids, provide an ideal medium. Similarly, carbon nanomaterials like carbon nanotubes (CNTs) and graphene exhibit extraordinary mechanical, electrical, and optical characteristics, rendering them as highly desirable options for augmenting the efficiency of liquid crystals across various applications.

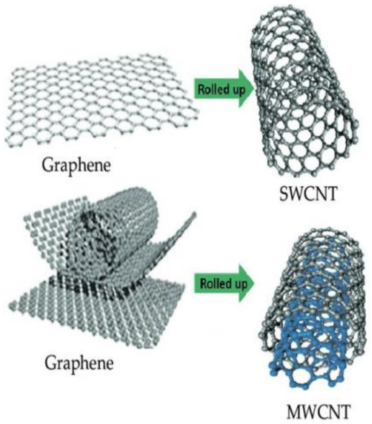

Figure 1.(**a**) Schematic diagram of SWCNT and MWCNT, (**b**) the MWCNT wrapped with poly (3-hexylthiophene) [9]

By integrating carbon nanomaterials into liquid crystal matrices, we unlock immense possibilities for developing advanced materials with customized functionalities and enhanced performance capabilities.

1.2. Problem Statement

There are various obstacles and areas of study that need to be tackled despite the considerable potential of composites that encompass liquid crystals infused with carbon nanomaterials. One of these challenges involves effectively dispersing the carbon nanomaterials within the liquid crystal medium to achieve a uniform arrangement and prevent aggregation. Additionally, achieving controlled alignment of the dispersed carbon nanomaterials is crucial to optimize their characteristics and interactions with the liquid crystal host. Moreover, it is essential to delve into the ramifications of incorporating carbon nanomaterials on the structural, electrical, and optical properties of liquid crystals, while also exploring their potential applications in emergent technologies.

1.3. Objectives of the Study

The primary objective of this research study is to provide a comprehensive overview of the advancements and prospects of composites consisting of carbon-nanomaterial-dispersed liquid crystals. Specifically, the study aims to:

(a) Explore the synthesis methods employed for the preparation of these composites, including dispersion techniques and alignment strategies.

(b) Investigate the effects of carbon nanomaterial incorporation on the structural, electrical, and optical properties of liquid crystals.

(c) Discuss the potential applications of carbon-nanomaterial-dispersed liquid crystal composites in optoelectronic devices, sensors, and energy storage systems.

(d) Highlight recent experimental findings and theoretical studies that contribute to the understanding and advancement of these composites.

(e) Identify prospects and challenges in the field, including scalability, stability, and integration of these composites into practical device architectures.

By addressing these objectives, this research study aims to provide valuable insights into the advancements and prospects of composites consisting of carbon-nanomaterial-dispersed liquid crystals, paving the way for further research and development in this exciting field.

2. Synthesis Methods for Carbon-Nanomaterial-Dispersed Liquid Crystal Composites

2.1. Dispersion Techniques

The successful dispersion of carbon nanomaterials, such as carbon nanotubes (CNTs) and graphene, within liquid crystal matrices is crucial for achieving homogeneous distribution and maximizing their potential benefits. Various dispersion techniques have been employed to ensure effective dispersion, including:

(a) Sonication: Ultrasonication is a commonly used technique to disperse carbon nanomaterials in liquid crystals. The application of high-frequency ultrasound waves helps to break down agglomerates and promote uniform dispersion.

(b) Surfactant: Assisted Dispersion: Surfactants can be used to stabilize and disperse carbon nanomaterials in liquid crystals. Surface functionalization of carbon nanomaterials with surfactant molecules enhances their compatibility with the liquid crystal host, preventing agglomeration and improving dispersion.

(c) Polymer: Assisted Dispersion: Polymers can be utilized to facilitate the dispersion of carbon nanomaterials in liquid crystals. Functionalized polymers can act as compatibilizers, providing a bridge between the carbon nanomaterials and the liquid crystal matrix, leading to improved dispersion and stability.

(d) Electrostatic Assembly: Electrostatic interactions can be utilized to disperse carbon nanomaterials in liquid crystals. By modifying the surface charge of the nanomaterials or the liquid crystal host, electrostatic forces can be employed to achieve controlled dispersion.

2.2. Alignment Strategies

Alignment of the dispersed carbon nanomaterials within the liquid crystal medium is essential for optimizing the properties and interactions of the composites. Several alignment strategies have been developed to achieve controlled alignment, including:

(a) Surface Alignment: Surface treatment of substrates with alignment layers can induce the alignment of liquid crystal molecules and the dispersed carbon nanomaterials. Surface treatment techniques, such as rubbing or deposition of alignment layers, can orient the liquid crystal and nanomaterials in a desired direction.

(b) Electric Field Alignment: The application of electric fields can induce the alignment of liquid crystal molecules and the dispersed nanomaterials. By applying appropriate electric field parameters, the orientation and alignment of the composites can be controlled.

(c) Magnetic Field Alignment: Magnetic fields can also be utilized to align liquid crystals and the dispersed nanomaterials. By subjecting the composites to a magnetic field, the alignment can be controlled, enabling the manipulation of their properties.

(d) Shear Flow Alignment: Shear flow techniques, such as flow casting or spin coating, can induce alignment of the liquid crystal and nanomaterials. By controlling the flow conditions during the fabrication process, the alignment can be achieved in a specific direction.

The selection of appropriate dispersion techniques and alignment strategies depends on the specific carbon nanomaterials, liquid crystal host, and desired properties of the composites. The choice of these methods significantly influences the dispersion uniformity, alignment control, and overall performance of the carbon-nanomaterial-dispersed liquid crystal composites.

3. Structural, Electrical, and Optical Properties of Carbon-Nanomaterial-Dispersed Liquid Crystal Composites

3.1. Effects on Liquid Crystal Structure

The incorporation of carbon nanomaterials into liquid crystal matrices can significantly impact the structural properties of the composites. The interaction between the nanomaterials and the liquid crystal molecules can lead to changes in the molecular ordering, phase behaviour, and mesophase structure of the liquid crystals. The presence of carbon nanomaterials can induce a reorientation or distortion of the liquid crystal director, affecting the overall molecular arrangement. Additionally, the size, shape, and concentration of the nanomaterials play a crucial role in determining the structural modifications observed in the composites. Understanding and controlling these structural changes are important for tailoring the properties and performance of the carbon-nanomaterial-dispersed liquid crystal composites.

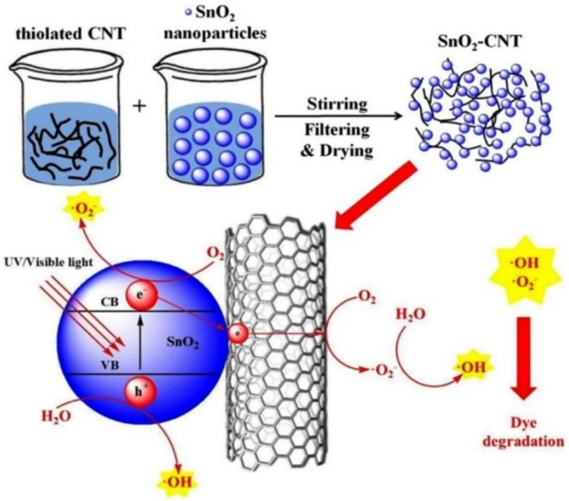

Figure 2. Schematic diagram of the preparation process of SnO_2/CNT NNs composites [23]

3.2. Electrical Conductivity Enhancement

One of the significant advantages of incorporating carbon nanomaterials into liquid crystals is the potential for enhancing the electrical conductivity of the composites. Carbon nanomaterials, such as carbon nanotubes and graphene, exhibit excellent electrical properties due to their high aspect ratio and unique electronic structure. When dispersed within the liquid crystal matrix, these nanomaterials form conductive networks, enabling the efficient transport of charge carriers. The percolation threshold, which represents the critical concentration at which a conductive network forms, can be tuned by adjusting the nanomaterial concentration. By optimizing the dispersion and alignment of carbon nanomaterials, the electrical conductivity of the liquid crystal composites can be significantly enhanced, opening opportunities for applications in flexible electronics, conductive coatings, and electronic devices.

3.3. Optical Properties and Light Manipulation

The incorporation of carbon nanomaterials into liquid crystals can also impact the optical properties of the composites, offering opportunities for light manipulation and optical device applications. Carbon nanomaterials possess unique optical properties, such as strong light absorption, broad wavelength range response, and tunable plasmonic properties. When dispersed in a liquid crystal matrix, these optical properties can be harnessed to control the transmission, reflection, and polarization of light. The alignment of the nanomaterials within the liquid crystal host further enables the manipulation of light propagation and birefringence. By designing and optimizing the dispersion, alignment, and concentration of carbon nanomaterials, the optical properties of the liquid crystal composites can be tailored for applications in displays, optical filters, waveplates, and other photonic devices.

The structural modifications, electrical conductivity enhancement, and optical properties of carbon-nanomaterial-dispersed liquid crystal composites are closely intertwined and depend on various factors, including the type and concentration of nanomaterials, dispersion techniques, alignment strategies, and liquid crystal characteristics. Understanding the relationship between these properties is crucial for harnessing the full potential of these composites and exploring their applications in a wide range of fields.

4. Applications of Carbon-Nanomaterial-Dispersed Liquid Crystal Composites

4.1. Optoelectronic Devices

The unique combination of carbon nanomaterials and liquid crystals in composites offers promising opportunities for optoelectronic devices. The enhanced electrical conductivity and tunable optical properties of these composites make them suitable for applications such as:

(i) Displays: Carbon-nanomaterial-dispersed liquid crystal composites can be used in the development of advanced displays, including flexible displays, wearable displays, and transparent displays. The improved conductivity and light manipulation capabilities enable higher resolution, faster response times, and improved viewing angles.

(ii) Photovoltaics: The integration of carbon nanomaterials into liquid crystal matrices can enhance the performance of solar cells and photovoltaic devices. The composites can improve charge carrier mobility, light absorption, and charge transport efficiency, leading to higher conversion efficiencies and improved device performance.

(iii) Light Modulators: The ability of liquid crystals to control the polarization and transmission of light, combined with the conductive properties of carbon nanomaterials, enables the development of light modulators and optical switches. These devices find applications in telecommunications, optical communications, and adaptive optics systems.

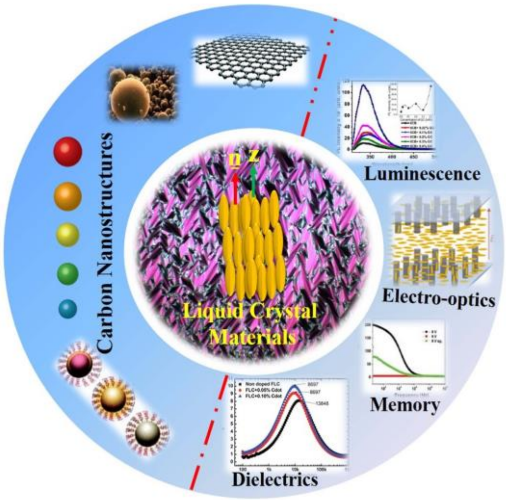

Figure 3. Figure showing the synergy between LCs and CNMs and their possible applications in diverse fields [17]

4.2. Sensors and Actuators

Carbon-nanomaterial-dispersed liquid crystal composites hold great potential for sensing and actuation applications. The unique properties of these composites can be exploited in the following areas:

(i) Chemical and Biological Sensors: The sensitivity of liquid crystals to external stimuli, combined with the enhanced electrical conductivity and surface functionalization capabilities of carbon nanomaterials, enables the development of high-performance chemical and biological sensors. These sensors can detect and respond to specific analytes, such as gases, biomolecules, and environmental pollutants.

(ii) Strain and Pressure Sensors: The mechanical flexibility and electrical conductivity of the composites make them suitable for strain and pressure sensing applications. The changes in electrical conductivity and alignment of the composites under strain or pressure can be utilized to measure and monitor mechanical deformations and forces.

(iii) Actuators: The tunable alignment and response of liquid crystals, coupled with the electrical conductivity and mechanical properties of carbon nanomaterials, enable the development of actuators. These actuators can be used in microelectromechanical systems (MEMS), robotics, and other applications requiring controlled motion and deformation.

4.3. Energy Storage Systems

Carbon-nanomaterial-dispersed liquid crystal composites show promise in energy storage applications, offering improvements in energy density, charge transport, and device performance. Potential applications include:

(i) Batteries: The incorporation of carbon nanomaterials in liquid crystal matrices can enhance the electrical conductivity and electrochemical properties of electrodes in batteries. This improvement can lead to increased energy storage capacity, faster charging rates, and improved cycling stability.

(ii) Supercapacitors: Carbon-nanomaterial-dispersed liquid crystal composites can be used in supercapacitors, enabling high energy and power densities. The high surface area and conductivity of carbon nanomaterials enhance charge storage and ion transport, resulting in improved capacitive performance.

(iii) Energy Harvesting: The tunable optical properties and light absorption capabilities of carbon nanomaterials dispersed in liquid crystals can be utilized in energy harvesting devices, such as photovoltaic cells and solar thermal collectors. These composites can enhance light absorption and improve energy conversion efficiency.

The applications of carbon-nanomaterial-dispersed liquid crystal composites in optoelectronic devices, sensors, actuators, and energy storage systems highlight their versatility and potential impact in various technological fields. Continued research and development in these areas will contribute to the realization of advanced devices and systems with improved performance and functionality.

5. Experimental Findings and Theoretical Studies

5.1. Enhanced Electrical and Optical Performance

Experimental studies have demonstrated the enhanced electrical and optical performance of carbon-nanomaterial-dispersed liquid crystal composites. These findings highlight the potential for improving the conductivity, light manipulation, and device performance of these composites. Several key experimental findings include:

(i) Electrical Conductivity Enhancement: The incorporation of carbon nanomaterials, such as carbon nanotubes and graphene, into liquid crystal matrices has been shown to significantly enhance the electrical conductivity of the composites. Conductivity measurements have revealed that the percolation threshold, at which a conductive network forms, can be precisely controlled by adjusting the nanomaterial concentration and alignment. The conductivity enhancement enables applications in flexible electronics, conductive coatings, and electronic devices.

(ii) Tunable Optical Properties: The dispersion and alignment of carbon nanomaterials within liquid crystals offer opportunities for tuning the optical properties of the composites. Experimental studies have demonstrated the control of light transmission, reflection, polarization, and absorption by manipulating the concentration, size, and alignment of the carbon nanomaterials. These findings pave the way for applications in displays, optical filters, and other photonic devices.

(iii) Improved Device Performance: Carbon-nanomaterial-dispersed liquid crystal composites have shown improved device performance in various applications. For example, in optoelectronic devices such as solar cells and photodetectors, the enhanced electrical conductivity and light absorption capabilities of the composites have resulted in higher conversion efficiencies and improved device performance. Similarly, sensors and actuators incorporating these composites have exhibited increased sensitivity, faster response times, and enhanced functionality.

5.2. Theoretical Modelling and Simulation

Theoretical modelling and simulation studies have played a crucial role in advancing the understanding of carbon-nanomaterial-dispersed liquid crystal composites. These studies provide valuable insights into the underlying mechanisms, interactions, and properties of the composites. Key areas of theoretical research include:

(i) Molecular Dynamics Simulations: Molecular dynamics simulations have been employed to investigate the dispersion and alignment of carbon nanomaterials within liquid crystal matrices. These simulations help understand the influence of nanomaterial properties, concentration, and external factors on the composite structure and properties. They provide atomistic-level details of the interfacial interactions and collective behaviour of the composites.

(ii) Continuum Modelling: Continuum models, such as the effective medium theory and percolation models, have been utilized to predict the electrical and optical properties of carbon-nanomaterial-dispersed liquid crystal composites. These models allow for the estimation of conductivity, dielectric response, and optical behaviour based on the composite's composition and morphology. Continuum modelling provides insights into the macroscopic behaviour and performance of the composites.

(iii) Density Functional Theory (DFT): Density functional theory calculations have been employed to study the electronic structure, bandgap, and charge transport properties of carbon-nanomaterial-dispersed liquid crystal composites. DFT-based simulations enable the exploration of the electronic properties and charge transfer mechanisms at the nanoscale level, aiding in the understanding of the conductivity enhancement and optical response of the composites. The combination of experimental findings and theoretical studies provides a comprehensive understanding of the carbon-nanomaterial-dispersed liquid crystal composites, bridging the gap between fundamental insights and practical applications. The synergy between experimental and theoretical approaches contributes to the advancement of these composites and guides future research endeavours.

6. Future Prospects and Challenges

6.1. Scalability and Large-Scale Production

One of the key challenges for carbon-nanomaterial-dispersed liquid crystal composites is the scalability and large-scale production of high-quality materials. Currently, the synthesis and fabrication processes for these composites are often labor-intensive and time-consuming. Efforts are needed to develop scalable and cost-effective manufacturing techniques that can produce composites with consistent properties on a large scale. Additionally, the optimization of dispersion techniques, alignment strategies, and process parameters is crucial to ensure uniformity and reproducibility in large-scale production.

6.2. Stability and Long-Term Performance

The long-term stability and performance of carbon-nanomaterial-dispersed liquid crystal composites are critical for their practical applications. Challenges arise from issues such as agglomeration, phase separation, and degradation over time. Carbon nanomaterials tend to form agglomerates, affecting the dispersion quality and leading to non-uniform properties in the composites. Moreover, interactions between the nanomaterials and liquid crystal host, as well as external factors such as temperature and humidity, can impact the stability of the composites. Future research should focus on addressing these challenges to ensure the long-term stability and reliability of the composites in real-world applications.

6.3. Integration into Device Architectures

Integrating carbon-nanomaterial-dispersed liquid crystal composites into practical device architectures is another important aspect for their future prospects. The compatibility of these composites with existing device fabrication processes and architectures needs to be considered. Efforts should be made to develop suitable deposition methods, patterning techniques, and interface engineering strategies to ensure efficient integration and reliable performance in device applications. Additionally, the design and optimization of device architectures to fully exploit the enhanced electrical and optical properties of the composites will be crucial for achieving high-performance devices.

6.4. Multifunctionality and Synergistic Effects

Exploring the potential of carbon-nanomaterial-dispersed liquid crystal composites for multifunctional applications and understanding the synergistic effects among the constituent materials are areas of future research. By incorporating additional functional components or modifying the composite structure, it is possible to achieve synergistic effects that enhance multiple properties simultaneously. For example, the combination of carbon nanomaterials with other nanomaterials, polymers, or nanoparticles may lead to unique properties or functionalities. Investigating these synergistic effects and developing tailored composite systems will broaden the scope of applications and advance the field.

6.5. Environmental Impact and Sustainability

As with any emerging technology, it is important to consider the environmental impact and sustainability aspects of carbon-nanomaterial-dispersed liquid crystal composites. The production and disposal of carbon nanomaterials can have environmental implications. Research efforts should focus on developing environmentally friendly synthesis methods, recycling approaches, and assessing the potential ecological risks associated with these composites. Furthermore, life cycle assessments and considerations of the environmental footprint can guide the development of sustainable manufacturing processes and ensure the responsible use of these materials.

Addressing the challenges and prospects outlined above will pave the way for the widespread adoption and practical applications of carbon-nanomaterial-dispersed liquid crystal composites. Continued research and collaboration among scientists, engineers, and industry partners are essential for advancing the field and unlocking the full potential of these materials in various technological domains.

7. Conclusion

7.1. Summary of Findings

In this paper, we have explored the advancements and prospects of composites consisting of carbon-nanomaterial-dispersed liquid crystals. The synthesis methods for these composites, including dispersion techniques and alignment strategies, have been discussed. We have also examined the structural, electrical, and optical properties of these composites, highlighting their effects on liquid crystal structure, electrical conductivity enhancement, and optical properties. Furthermore, we have explored the applications of these composites in optoelectronic devices, sensors and actuators, and energy storage systems. Experimental findings have demonstrated the enhanced electrical and optical performance of these composites, while theoretical studies have provided insights into their behaviour and properties.

7.2. Implications for Emerging Technologies

The advancements in carbon-nanomaterial-dispersed liquid crystal composites have significant implications for emerging technologies. These composites offer improved electrical conductivity, tunable optical properties, and enhanced device performance, making them promising candidates for a range of applications. Their integration into optoelectronic devices, such as displays, photovoltaics, and light modulators, can lead to higher resolution, faster response times, and improved energy conversion efficiencies. Additionally, the use of these composites in sensors, actuators, and energy storage systems can enable enhanced sensitivity, controlled motion, and higher energy densities. The unique properties of these composites position them at the forefront of advancements in various technological fields.

7.3. Future Directions for Research

While significant progress has been made in the field of carbon-nanomaterial-dispersed liquid crystal composites, there are several avenues for future research. Key areas for further investigation include:

(i) Scalability and large-scale production techniques to enable the practical implementation of these composites in commercial applications.

(ii) Addressing the challenges of stability and long-term performance to ensure the reliability and durability of the composites over extended periods.

(iii) Exploring the integration of these composites into device architectures, considering compatibility, fabrication processes, and optimizing the composite-device interfaces.

(iv) Investigating the synergistic effects and multifunctionality of the composites by incorporating additional functional components or modifying the composite structure.

(v) Assessing the environmental impact and sustainability of the composites, with a focus on developing environmentally friendly synthesis methods and recycling approaches.

(vi) Advancing theoretical modelling and simulation techniques to further understand the behaviour, properties, and interactions of these composites at the nanoscale level.

By addressing these research directions, the field of carbon-nanomaterial-dispersed liquid crystal composites will continue to progress, unlocking new possibilities and applications. The collaborative efforts of researchers, engineers, and industry partners will play a crucial role in shaping the future of these materials and driving technological advancements in diverse fields.

In conclusion, the advancements in carbon-nanomaterial-dispersed liquid crystal composites have demonstrated their potential for revolutionizing various technological domains. These composites offer enhanced electrical and optical properties, paving the way for the development of high-performance devices and systems. With further research and development, these composites hold promise for enabling breakthroughs in emerging technologies and contributing to a sustainable and technologically advanced future.

By examining the advancements and prospects of composites consisting of carbon-nanomaterial-dispersed liquid crystals, this research paper provides valuable insights into the potential applications and performance improvements achieved in this field. The integration of carbon nanotubes and graphene into liquid crystal matrices offers opportunities for developing next-generation optoelectronic devices, sensors, and energy storage systems. The paper presents a comprehensive analysis of the structural, electrical, and optical properties of these composites, highlighting the promising experimental findings and theoretical studies. Furthermore, the identification of future prospects and challenges aims to guide future research and development efforts toward scalable production, enhanced stability, and successful integration of these composites into practical device architectures. The research outlined in this paper contributes to the advancement of carbon-nanomaterial-dispersed liquid crystal composites and their potential impact on emerging technologies.

Declarations

Source of Funding

The study has not received any funds from any organization.

Competing Interests Statement

The authors have declared no competing interests.

Consent for Publication

The authors declare that they consented to the publication of this study.

Authors' Contributions

All the authors took part in literature review, research and manuscript writing equally.

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