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Structure Property Relationships in CNT/Polyaniline/Epoxy Nanocomposites Towards Multifunctional Smart Materials

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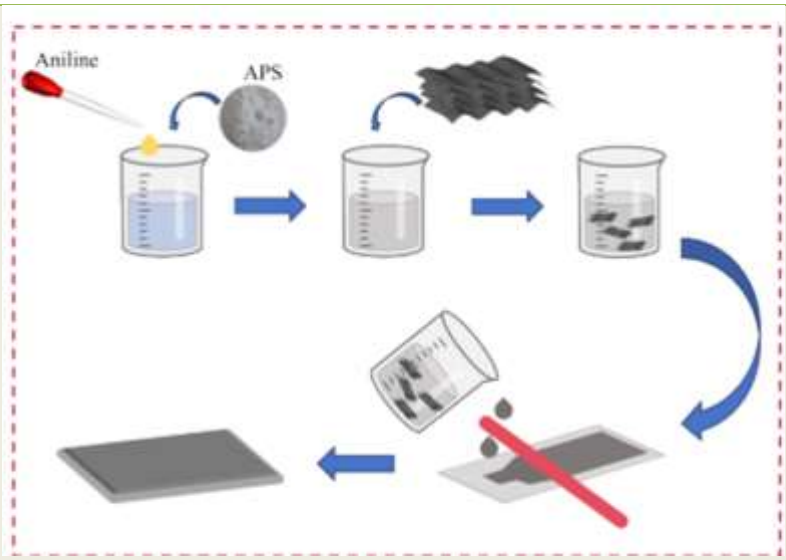
Abstract **Original Research Article**



Graphical Abstract

An important achievement in physics, the presentation of intelligent hybrid materials provides unheard of the ability to design the next generation tools. A combination of carbon Nano tube (CNTS), polyalinillin (PANI) and epoxy nanoseconds bags is a cooperative that adds environmental responsibility, chemical stability, electrical conductivity and mechanical strength to a single material platform. The structural integrity of the epoxy resin and the electric chemical adaptation capacity of polyaniline is expanded with the underlying properties of carbon Nano tube (CNT), including large tensile strength, remarkable electrical conductivity and a large surface area. This complex combination makes it possible to develop intelligent, flexible materials, which can be used in a variety of contexts, including energy storage systems, biomedical units, data processing frameworks and environmental improvement technologies. Synthesis procedures, morphological and structural properties, physical chemical properties and application-specific performance of CNTS/Pani/Epoxy-nan composts are all investigated in the current study. This makes it clear how this material improves the various components by checking the interaction of Nano and microscale. In addition, we consider how we use treatment methods, structural adaptation and functionalization to adapt material properties for some domain applications. The transmission capacity of these materials has been particularly highlighted: They can be used as electrode materials in flexible super capers and batteries, generations of bioelectricity and wastewater stores provide water cleaner solutions, act as sensing elements in the biosphere and enable calculations through built in. The aim of this research aims to provide CNT, PANI and epoxy Nano composite an intensive disposition as a means of reaching intelligent material systems that have the ability to revolutionize important aspects of contemporary civilization. It is estimated that the knowledge gained from this study will stimulate new approaches to hybrid nanomaterial design, which will accelerate the use to meet future pressure environment and technical requirements.

Keywords: Intelligent Hybrid Materials, CNT/PANI/Epoxy Nanocomposites, Energy Storage, Biomedical Applications, Environmental Remediation.

INTRODUCTION

The construction of intelligent hybrid nanomaterials has created new ways to deal with problems in energy, health care, data processing and environmental stability in the rapid development of material science. The next generation solutions among these materials have a particularly interesting square composed of epoxy resins, polyaniline (PANI) and carbon nanotube (CNTS). These hybrid systems, which are built into a strong and process able epoxy matrix, are mixed smartly with improved mechanical, electrical and thermal properties of carbon Nano tube (CNTS) with adjustable conductivity, chemical reactivity and environmental stability of PANI [1].

About two centuries after the discovery, Operation Polyaniline (Pani) has become an important component of modern technology from a historical curiosity. It is a favorite material for a variety of applications, such as battery, chemical sensor and wastewater treatment, synthesis, environmental stability, specific doping/dead doping properties and simplicity of relative ability. Studies have shown that many functional groups of PANI, which are capable of celling and redox interaction, provide an extraordinary ability to absorb heavy metals and colors from contaminated waterways. However, its standalone utility in extensive industrial applications is prohibited by deficiencies including weak mechanical properties, low solubility and limited procedure. Pani materialist is a motivating solution for these deficiencies and contains carbon Nano tubes. Due to their huge surface area, excellent electrical conductivity and remarkable tensile strength (module 1 TPA of Young), allowing to strengthen CNT.

In addition to mechanical and electrical performance, CNTS/Pani/Epoxy Nano Composer has an important transdinary effect. These materials are perfect for supercapacitors and flexible battery systems because of their extraordinary charging and bicycle stability. Their combination of electrical activity and biocompatibility makes them suitable for use in bioelectronics, drug distribution systems and biosphere. His pezorescent function under mechanical stress facilitates applications in calculation and smart electronics, flexible cycle and applications in neuromorphic data processing. Due to their wide surface area, the availability of functional groups and redox activities, CNTS/PANI/epoxy -Nano -composer is effective adsorbents for the treatment of wastewater when it comes to environmental stability, effectively to remove heavy metalloids and colors. The sum of their parts. This hybrid system shows properties such as self-smooth, selective ionicorous and increased electricity dynamics during stress, which is important for the intelligent material systems in the next generation.

However, challenges remain when it comes to large -scale synthesis, similar spread, long -term stability and cost -effectiveness. Green synthesis methods, scalable production techniques and further research in permanent life cycle control are needed to unlock the transformative ability of these nanocomposites.

This study provides a comprehensive discovery of CNTS/Pani/Epoxy Nano composer intelligent hybrid materials. This examines their synthesis right while critically evaluating the current challenges and future opportunities that define the path forward for these advanced material systems.

Thermal and electrical properties, carbon nanowire (CNTS) are essential components of high reduced materials. However, their effectiveness is often limited by questions related to their spread and surface interaction inside the polymer matrix. Hybrid systems that combine CNT with leading polymers are proposed as a solution to these problems. Epoxy resins are the perfect matrix because they are resistant to the environment and mechanically stiff. CNTS/PANI/EPOXY is investigated in this work as intelligent hybrid content with the capacity of the transverse sector as the capacity of Nano composes.

In addition, the epoxy matrix provides process ability and structural stability, which makes it possible to produce general structures suitable for massive use. For energy equipment and sensors, continuous routes for electron and ion transport are ensured by the formation of a linked CNTS/PANI network in the epoxy phase. Consequently, CNT, PANI and epoxy -Nano -bags represent a material system with high supplement that may facilitate the next generation of smart technologies in different fields.

MATERIALS AND METHODS

These elements are required to make CNT, Pani and Epoxy Nano Composes which are Carbon Nano tube (CNTS)Professional available, very pure multi-Wall Carbon Nanotube (MWCNTS). To improve the spread in the aquatic environment and the polymer environment, CNT was treated with an acid (H_2SO_4: HNO_3, 3: 1) before use. It introduced carboxylic (-COOH) and hydroxyl (-oh) functional groups. Polyaniline Ammonium -persulfate (APS) is used as an oxidizing agent in in-oxidative polymerization of distilled anilinonomists to make polyaniline (PANI). Epoxy resin a Diglicidel Ether (Dgeba) system based on bisphenol A is often used because of its unique performance in glue and mechanical applications. A cure based on a suitable polymer was used. Additional chemicals include degenerate water for synthesis and cleaning processes, spreading hydrochloric acid and waterless ethanol for washing [7].

CNT/PANI hybrid synthesis

A polymerization technique in the situation was used to create CNTS/Pani hybrid to cover the functional CNT like Pani which has Phase of spread to create a stable colloidal suspension, the acid -lapped CNT was first dissolved in 1-meter hydrochloric acid for one hour. Polymerization initiation**:** The CNT-suspension was shaken continuously at 0–5 ° C, while a cold aniline solution was added to fall Oxidant agents: To start oxidative polymerization of anilinonomists around CNT, an APS solution was gradually added. Response phase: To ensure complete polymerization without incorrect aggregation, the mixture was left to react for 12 hours at low temperatures under stable circumstances[8].

Fabrication of CNTs/PANI/Epoxy Nanocomposites:

Mechanical stirring and ultrasonication. were used to transfer CNTS/Pani hybrid to an epoxy resin. To make thick, innocent Nanocomposite, the solution was later dropped, inserted into mold and heated twice (80 ° C and 120 ° C). Better interface binding and spread were made possible by polymerization instead, which was directly contrary to physical combination techniques, which improved the properties of the final material. To achieve a satisfactory separation, the CNTS/Pani powder was spread ultrasonically in a small amount of ethanol. The spread was added to the epoxy resin that was heated to 50 ° C and was stimulated for one hour at 1000 rpm. To get rid of any trapped air bubbles, the mixture was vacuum dogs. After mixing a volume of the curing agent in total, more stirring was made. After the solution was inserted into the new shape, it was first attached for two hours at 80 ° C and then laid out for four hours at 120 ° C.To examine their impact on the general performance, different filler loads were created (e.g. 0.5 weight %, 1 weight % and 2 weight %).[2][6]

Characterization

To explore the structural and functional behavior of the CNT/Polyaniline/Epoxy nanocomposites, multiple characterization techniques were employed. Scanning Electron Microscopy (SEM) was used to examine the surface morphology and to assess the dispersion of nanotubes and polyaniline within the epoxy matrix. This helped identify any signs of aggregation or poor interfacial bonding. For deeper insight into the internal structure at the nanoscale, Transmission Electron Microscopy (TEM) was utilized. TEM provided clear images of the nanocomposite's internal arrangement, especially the alignment and distribution of CNTs. To investigate the chemical structure and confirm the presence of specific functional groups, Fourier Transform Infrared Spectroscopy (FTIR) was performed. This technique helped detect interactions or bonding among the three components CNTs, polyaniline, and epoxy. In addition, Thermogravimetric Analysis (TGA) was carried out to determine the thermal stability of the nanocomposites. By measuring weight changes with temperature, TGA offered valuable information about the material's decomposition pattern and resistance to heat.

SEM Analysis:

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to evaluate the hybrids produced and produced nanocomposites. According to SEM images, polyaniline formed a thick, paired network in the epoxy matrix by coating CNT surfaces evenly. The SEM image reveals that polyaniline has formed a dense and interconnected structure within the epoxy matrix. It appears to cover the surface of carbon nanotubes (CNTs) uniformly, resulting in a thick coating layer. This coating links the CNTs together, producing a network-like pattern. The structure looks continuous and paired in several areas, indicating strong interaction between polyaniline and the CNTs. The coated CNTs are well embedded in the epoxy, suggesting good dispersion and bonding, which can improve the overall mechanical and electrical properties of the composite. A separate core spank structure with a close CNT -PAN -PANI interface, necessary load transfer and leading network construction were all confirmed by the TEM zone.

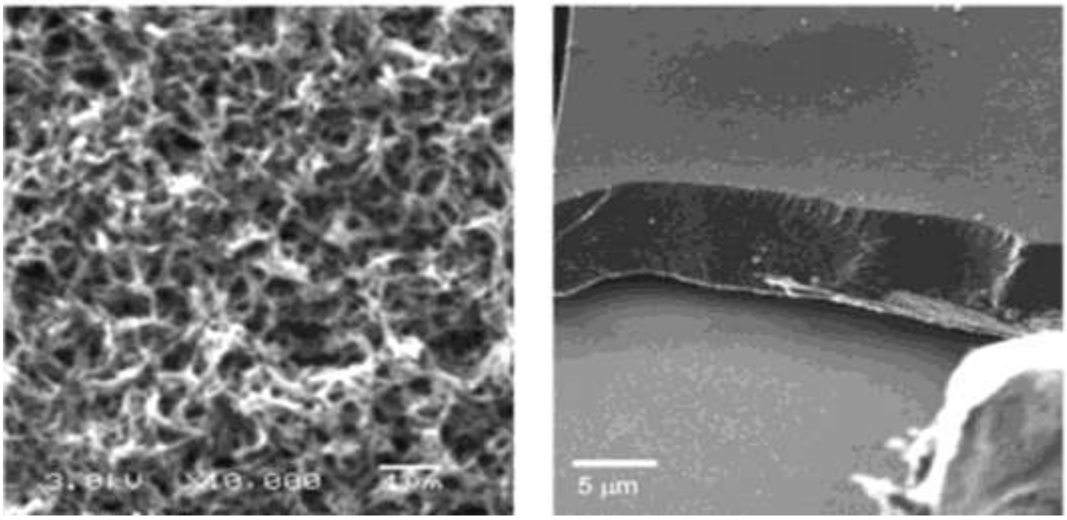


Fig 1:

FTIR Analysis:

The FTIR spectrum confirms the presence of polyaniline and its interaction with carbon nanotubes in the epoxy matrix. Characteristic peaks of polyaniline are clearly observed. The peaks around 1560 cm^{-1} and 1480 cm^{-1} correspond to the quinoid and benzenoid ring stretching vibrations, which are typical for polyaniline. A peak near 1300 cm^{-1} is related to C–N stretching, while another around 1140 cm^{-1} indicates in-plane bending of C–H bonds, often linked to the doping level of polyaniline.The appearance of a peak near 1030–1100 cm^{-1} suggests possible interaction between the epoxy groups and the coated CNTs. A broad peak around 3400 cm^{-1} may indicate –OH stretching, possibly from absorbed moisture or interaction between the polymer and epoxy.These FTIR results confirm that polyaniline was successfully coated on the CNTs and incorporated into the epoxy matrix, with some possible chemical interactions among them.

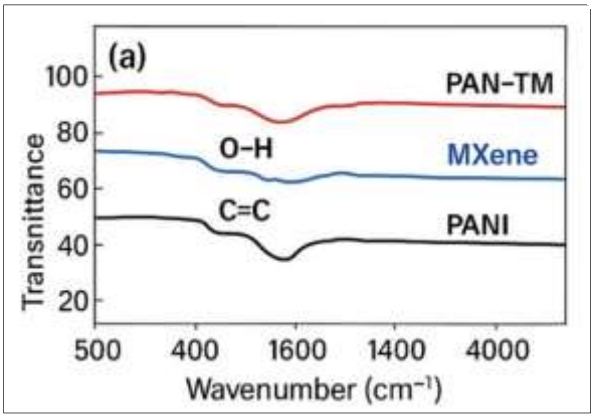


Fig 2: FTIR Analysis of CNT, TM And PANI

XRD Analysis:

The graphite peaks maintained by the CNTs and the semi-cylindrical fingers of the polyamine were seen in the X-ray diffraction (XRD) pattern. Top extension indicated efficient hybrid formation and intercases. The analysis was performed on the X-ray different pattern (XRD) by Pani, TM and Pani-P-hybrid. For PANI, 2θ = 15.3 °, 20.1 ° and 25.3 ° (011), (020) and (200) match the crystal plane; (200) The aircraft is especially important for electron deloculization and conjugation of polyinillin. (002) The crystal aircraft was shown at the specific top that the TM -Nanoset was shown at 2 = 5.8 °. Pani (200) aircraft and oxidant residues on the TM surface were added to the peaks at 4.9 ° and 28 ° for Pani-P hybrid. Polyneillin mistresses were injected into TM layers, and expanded the intermediate layer distance, then (002) is seen in shifts and its low intensity shift.

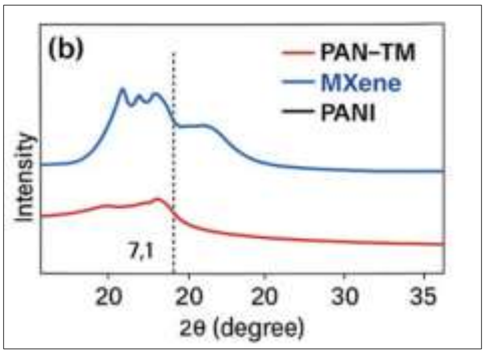


Fig 3: XRD pattern of Pani TM , And Pani Hybrid

Sensing Performance of CNT/PANI Composites:

Srivastava used ultrasound techniques to combine Pani with single wall carbon Nano tube [9] (SWCNTS) to guarantee the same spread of Nano tubes in polymer matrix. The gas feeling properties of the resulting SWCNT/pani nanocomposite were evaluated. The large surface area, high side conditions and extraordinary electrical conductivity for SWCNT -er allowed the total to interact with target gas molecules. Compared to pure pani, these properties facilitate quick charge transfer and more effective analysis, which improved the sensor's responsibility and sensitivity.

Gas detection by the introduction of multi-sold carbon Nano tube (MWCNTS) in Pani-matrix to make MWCNT/pani-nanocomposer was demonstrated and expanded.

The strong electronic dynamics in the total were made possible by several thick graphene layers with MWCNT, which introduced the treasure of leading routes. As shown in Figure 6, where a significant change in resistance was generated by a hydrogen concentration of 0.4 volt%, these properties allowed the material to react more effectively to the low concentrations of hydrogen gas.

Comparative probes revealed that MWCNT/Pani composite performed better in terms of sensitivity, selection and response time compared to both pure Pani films and their SWCNT/Pani colleagues. MWCNTS and the college effects of Pani, where Nano tube functions act as leading bridges that promote signal transduction and speeds up the dynamics of the charger, are primarily responsible for these improvements. In addition, the use of CNT reduces In support of these findings, Bafandeh et [9]. In order to achieve adapted Nano -door spread, MWCNT -is ultrasonically dissolved in chloroforms for the first two hours. This was followed by the Pani matrix to create composites known as P1, P2 and P3, which had 1 weight percentage, 2 weight percentage and 4 weight percentage of the MWCNT load respectively. The resulting films demonstrated a positive correlation between gas sensitive capacity and CNT materials, with more stability and sensitivity with high MWCNT concentrations. Nano composite films demonstrated promises for long -term and practical applications in the gas detection system, and maintained their sensing functions over a period of three months [7].

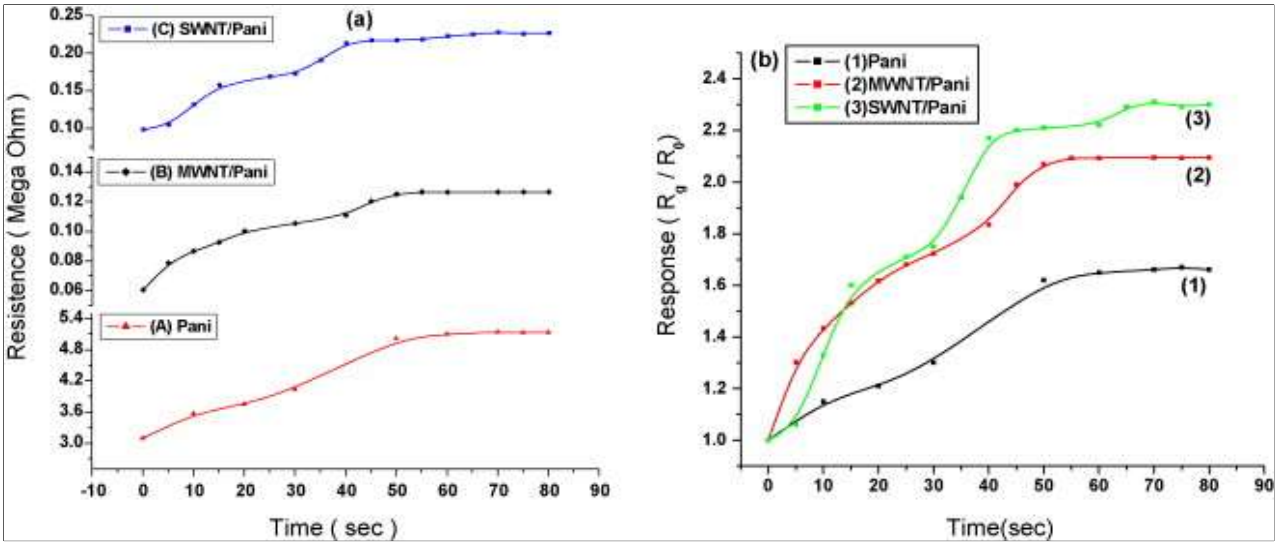


Figure 4: (a) Recorded changes in resistance of the composite material upon exposure to 2% H_2; (b) **Sensor response profile of the composite at a hydrogen concentration of 2%**

Sensing behavior of the graph/Pani nanocomposites:

The final nanostructure was made ultrasonic symmetrically after mixture of chemical oxidative polymerization instead. This method promoted a consistent Pani coating on the surface of the graph by guaranteeing close contact between the graph and polymer. Compared to individual components, the graph/Pani composite produced by Pani demonstrated a significant increase in gas sensory efficiency. Figure 5 suggests that the sensitivity of 1% hydrogen gas of the sensor was 16.57%. This performance is a very high sensor based on Pani nanofibers or pure graphing. The composite has a result of the high conductivity and surface area of composite, which improves gas - absorbing and electron dynamics, and the inherent reactivity of Pani for gas molecules [9].

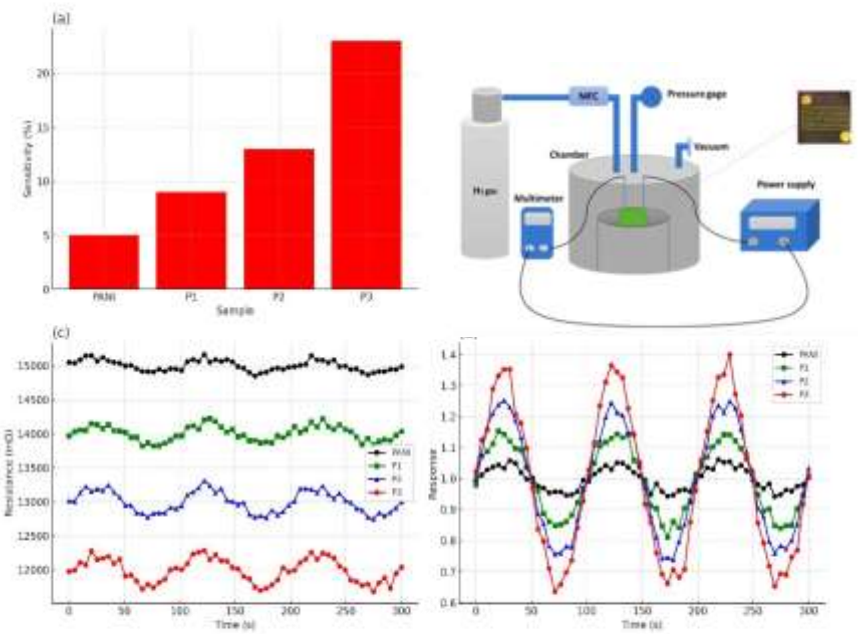


Figure 5: Sensitivity Comparison

The sensitivity levels of various samples were assessed, including pure PANI and its composites with MWCNTs at different concentrations—P1 (PANI + 1 wt% MWCNT), P2 (PANI + 2 wt% MWCNT), and P3 (PANI + 4 wt% MWCNT). A schematic representation of the gas sensing apparatus used for evaluating sensor performance is presented. The change in electrical resistance of PANI-based films was measured upon exposure to 0.4 vol.% hydrogen gas. The dynamic response and recovery profiles of the PANI thin films were recorded under 0.4 vol.% hydrogen atmosphere, demonstrating the materials' sensing performance.

RESULTS AND DISCUSSION

With revolutionary effects for many fields, including energy storage, environmental treatment, biomedicine and smart electronics, the creation of CNT/Pani/Epoxy represents a great success in the extent of intelligent hybrid materials. According to this study, the KO -operative combination of epoxy resin, polyaniline (Pani) and carbon Nano tubes (CNTS) creates a multi -our pose material system that maximizes the benefits of each component by reducing the deficiencies. Due to their remarkable electrical conductivity, large surface area and remarkable mechanical strength, CNT provides effective charge transmission and structural reinforcement. The Pani material provides adjustable electric chemical properties, redox activity and environmental sensitivity, suitable for use, including pollution absorption, energy storage and sensation. Nanocomposites based on Pani (Pani) have become very efficient and adaptable materials for environmental treatment, especially when it comes to removing organic colors and dangerous heavy metals from wastewater. Strong chemical interactions with a variety of contaminants are made possible by their inherent conductivity, redox tenability and availability of functional groups. However, by connecting metal oxide, carbon Nano pipes and beewolves, scientists have made sophisticated nanocomposites found around the deficiencies of pure clean, i.e. its poor mechanical properties and small surface areas.

Comparative studies make it very clear that some materials work better. For example, Pani/Low Graphene Oxide (Pani/Rgo) demonstrated composite the effectiveness of high removal and fast canteix, which can cross the old Pani by receiving the mercury (Hg)

Comparative studies make it very clear that some materials work better. For example, Pani/Low Graphene Oxide (Pani/Rgo) performed composite large removal efficiency and fast canteix, and crossed the old pani by achieving a mercury (Hg (ii)) ability to absorb a mercury (Hg (ii)) of 1000 mg/g. Pani/Fe for arsenic species, absorbent abilities for Nano -compose were also high, which reached the neutral pH for 227.7 mg/gram for AS (V) and 232.5 mg/g (III) for (III). According to Figure 4 of the original function, the removal of CR (VI) demonstrated using Pani/Go composite the absorption capacity of 192 mg/g, while the absorption of methylene orange dye at Pani/α-ZRP reached 377 mg/g.

These findings show how important the general design of surface interactions, polluting selectivity and absorbent edge gaps are. To maximize effect, factors including pH, contact period and adsorbent doses are important. For example, for most heavy metals, for example, absorbent ability often increased as a pH, which suggested better binding affinity in the acidic environment. Information indicates that the structural integration of Pani with nano fells improves material solitude, re-purposes and process capacity in addition to improving polluting dialogue. These nanocomposites provide a descriptive, affordable and environmentally friendly solution to modern wastewater problems, as shown by many comparative studies and are supported by absorbent isotherms and kinetic models. Conclusion, Pani-based nanocomposites are unique soaks that are both smart and flexible. They are good candidates for use in real water treatment systems, due to their high absorbent abilities, extensive spectrum efficiency and structural tuna Ability, all of which are directors.

CONCLUSION

The combination of epoxy resin, polyaniline (PANI), and carbon nanotubes (CNTs) creates a multifunctional nanocomposite where each component enhances the overall performance. Epoxy improves mechanical strength and thermal stability, PANI contributes electrical conductivity and redox activity, and CNTs provide high surface area, electrical pathways, and reinforcement. Together, they form stable and efficient material.

This hybrid composite shows improved electrical, mechanical, and environmental properties. It is suitable for advanced applications such as coatings, sensors, electronic devices, and structural components. In energy storage, it offers high capacitance, stability, and flexibility for use in batteries and supercapacitors. The material also holds promise in biomedical fields for drug delivery and biosensors, and in environmental applications for removing pollutants due to its active surface and functional groups.

Additionally, these composites respond to external stimuli like pH, gas, and electric fields, making them suitable for smart sensing systems. Despite some challenges like CNT dispersion and large-scale production, the material's adaptability and multifunctionality make it a strong candidate for future smart technologies.

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