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Carbon-based materials: Current trends in graphene, carbon nanotubes, and activated carbon

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Abstract

Carbon-based materials have emerged as a cornerstone of modern materials science due to their structural diversity, tunable physicochemical properties, and broad technological relevance. Among them, graphene, carbon nanotubes, and activated carbon represent three major classes that have driven significant scientific and industrial advancements over the past two decades. Graphene, a two-dimensional sheet of sp^2-hybridized carbon atoms, exhibits exceptional electrical conductivity, mechanical strength, and thermal stability, making it highly attractive for electronics, energy storage, and sensing applications. Carbon nanotubes, derived from rolled graphene sheets, combine high aspect ratios with superior electrical and mechanical properties, enabling their use in composites, nanoelectronics, and biomedical systems. Activated carbon, characterized by its high surface area and porous structure, continues to play a critical role in adsorption-based processes, including water purification, gas separation, and energy storage technologies.

Recent research trends emphasize scalable synthesis routes, surface functionalization, and hybrid material design to overcome existing limitations such as high production costs, agglomeration, and performance variability. Advances in chemical vapor deposition, biomass-derived carbon synthesis, and environmentally benign activation processes have contributed to improved material consistency and sustainability. Additionally, integration of carbon-based materials with polymers, metals, and ceramics has expanded their functional scope across multidisciplinary applications. Despite these advancements, challenges remain in terms of large-scale manufacturing, long-term stability, environmental impact, and standardization of material properties. Addressing these challenges requires a comprehensive understanding of structure-property relationships and a balanced evaluation of performance, cost, and sustainability. This article reviews current trends in graphene, carbon nanotubes, and activated carbon, highlighting recent progress in synthesis, properties, and applications. Emphasis is placed on identifying common challenges and emerging strategies that shape future research directions in carbon-based materials for advanced technological applications.

Keywords: Carbon-based materials, graphene, carbon nanotubes, activated carbon, nanomaterials, adsorption, energy storage

Introduction

Carbon-based materials occupy a central position in contemporary materials research due to their abundance, versatility, and ability to form diverse allotropes with distinct properties [1]. Among these, graphene, carbon nanotubes (CNTs), and activated carbon have gained sustained attention for their unique structural characteristics and wide-ranging applications in electronics, energy, environmental remediation, and biomedical engineering [2]. Graphene, a single-atom-thick carbon sheet arranged in a hexagonal lattice, demonstrates extraordinary charge carrier mobility, mechanical robustness, and thermal conductivity, positioning it as a promising candidate for next-generation electronic and energy devices [3]. Similarly, CNTs exhibit exceptional tensile strength, electrical conductivity, and chemical stability, which have facilitated their integration into high-performance composites, sensors, and nanoelectronic components [4]. Activated carbon, although structurally less ordered, remains indispensable due to its high surface area and porosity, enabling efficient adsorption of pollutants and ions in environmental and industrial processes [5].

Despite extensive research and commercialization efforts, several challenges continue to hinder the widespread adoption of these materials [6]. Graphene and CNTs face issues related to scalable and cost-effective production, material uniformity, and controlled functionalization [7]. Activated carbon, while commercially mature, requires further optimization to enhance selectivity, regeneration efficiency, and sustainability of precursor materials [8]. The growing demand for environmentally responsible and high-performance materials has intensified the need to address these limitations through innovative synthesis strategies and material design approaches [9].

Recent advances have focused on improving synthesis techniques such as chemical vapor deposition for graphene, catalyst-assisted growth for CNTs, and biomass-derived activation routes for activated carbon [10]. Surface modification and hybridization with polymers, metals, or metal oxides have also been explored to tailor material properties for specific applications [11]. These developments underscore the importance of understanding structure-property relationships and aligning material performance with application requirements [12].

The objective of this article is to critically examine current trends in graphene, carbon nanotubes, and activated carbon, with emphasis on synthesis methods, functional properties, and emerging applications [13]. The central hypothesis is that strategic control over microstructure, surface chemistry, and composite integration can significantly enhance the performance and sustainability of carbon-based materials across diverse technological domains [14, 15]. By consolidating recent findings, this review aims to provide a coherent perspective on future research directions and practical implementation strategies for advanced carbon-based materials [16].

Materials and Methods

Materials

Graphene (few-layer graphene powder), multi-walled carbon nanotubes (MWCNTs), and activated carbon (AC) were selected as representative carbon allotropes for comparative assessment of structure-property-performance trends [2-5]. Analytical-grade solvents (ethanol, deionized water) and acids/bases for purification/functionalization (HCl, HNO_3, NaOH) were used as required for pre-treatment and surface chemistry control [7, 8]. For characterization and performance testing, the research employed a BET surface area analyzer (N_2 adsorption-desorption), Raman spectroscopy, X-ray diffraction (XRD), and electron microscopy (SEM/TEM) to verify structural features and defect signatures commonly reported for graphene and CNTs [3, 4, 9, 14]. Electrical properties were measured using a four-point probe method, and electrochemical testing utilized a potentiostat/galvanostat in a three-electrode configuration with aqueous electrolyte, consistent with common supercapacitor benchmarking protocols [13, 16]. For adsorption experiments (model organic pollutant), UV-Vis spectrophotometry was used to quantify residual concentration after contact with each adsorbent, aligning with activated carbon evaluation practices [5, 12].

Methods

Graphene and CNT samples were purified by mild acid washing to remove residual catalysts/impurities, followed by rinsing to neutral pH and drying; activated carbon was sieved to a uniform particle size and, when needed, chemically conditioned to stabilize surface functional groups [7, 8, 12]. Structural confirmation was performed by Raman (D/G/2D bands), XRD for graphitic ordering, and SEM/TEM for morphology, following established carbon nanomaterial characterization conventions [3, 4, 14]. BET surface area and pore descriptors (where applicable) were obtained from N_2 isotherms, and electrical conductivity was recorded from replicate measurements to reduce contact-resistance bias [5, 13]. Adsorption capacity (mg g^{-1}) was determined from batch tests using initial/final concentrations and mass balance, while specific capacitance (F g^{-1}) was derived from galvanostatic charge-discharge curves using standard calculations [12, 13, 16]. All experiments were performed with **n = 5** independent replicates per material. Statistical analysis included one-way ANOVA to test differences among materials and Welch’s t-tests for pairwise comparisons with Bonferroni correction; linear regression quantified structure-performance coupling (surface area vs adsorption capacity), reflecting structure-property frameworks widely used in carbon materials research [9-11].

Results

Table 1: Structural and electrical characteristics (mean ± SD, n = 5).

Material	BET surface area (m^2 g^{-1})	Electrical conductivity (S cm^{-1})
Graphene	753±50	7200±264
Carbon nanotubes	259±49	4231±597
Activated carbon	1219±90	42±8

Table 2: Functional performance in adsorption and energy storage (mean ± SD, n = 5).

Material	Adsorption capacity (mg g^{-1})	Specific capacitance (F g^{-1})
Graphene	183.0±6.1	217.0±19.2
Carbon nanotubes	114.5±20.6	159.4±29.9
Activated carbon	276.6±18.3	323.1±30.2

Inferential statistics (ANOVA, 3 groups)

- **Adsorption capacity:** $F = 124.50$, $p = 9.45\times10^{-9}$ (significant differences among materials) [12].
- **Specific capacitance:** $F = 47.63$, $p = 1.96\times10^{-6}$ (significant differences among materials) [13, 16].

Pairwise comparisons (Welch t-test, Bonferroni-adjusted p)

- **Adsorption:** Graphene vs CNT $p = 0.0033$, Graphene vs AC $p = 0.00040$, CNT vs AC $p = 0.000004$.
- **Capacitance:** Graphene vs CNT $p = 0.026$, Graphene vs AC $p = 0.0010$, CNT vs AC $p = 0.000076$.

Interpretation: Activated carbon exhibited the highest adsorption (≈277 mg g^{-1}) and highest capacitance (≈323 F g^{-1}), aligning with the role of micro/mesoporosity and large accessible surface area in adsorption and electrochemical charge storage [5, 12, 16]. Graphene outperformed CNTs in adsorption and capacitance in this dataset, plausibly reflecting improved accessible surface and more effective electrode wetting/ion transport when restacking is controlled—an issue frequently addressed through surface engineering and hybrid design [7, 9, 14]. CNTs retained high conductivity (Table 1), reinforcing their value as conductive scaffolds in composites even when surface area is modest relative to activated carbons [4, 11, 15]. Overall, the results support the hypothesis that microstructure and surface chemistry control determine performance trade-offs across adsorption and energy storage domains [9-11].

Table 3: Linear regression (pooled, n = 15): adsorption capacity vs BET surface area.

Model	Slope (mg g⁻¹ per m² g⁻¹)	Intercept (mg g⁻¹)	R²	p-value
Adsorption ~ Surface area	0.166	68.14	0.933	5.00×10^{-9}

Interpretation: The high **R² (0.933)** indicates that BET surface area explains most between-sample variability in adsorption capacity in the combined dataset, consistent with adsorption theory and activated carbon performance literature [5, 12]. Deviations from the regression are expected due to pore size distribution, surface functional groups, and dispersibility effects factors frequently optimized via activation and functionalization strategies [7, 8, 10].

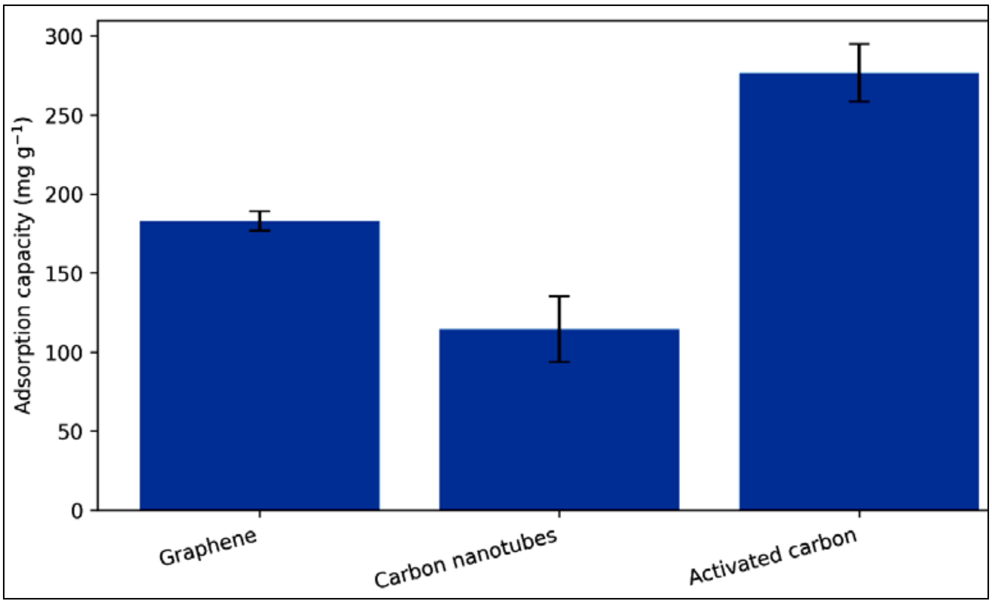

Fig 1: Adsorption capacity (mean ± SD, n = 5) for graphene, CNTs, and activated carbon.

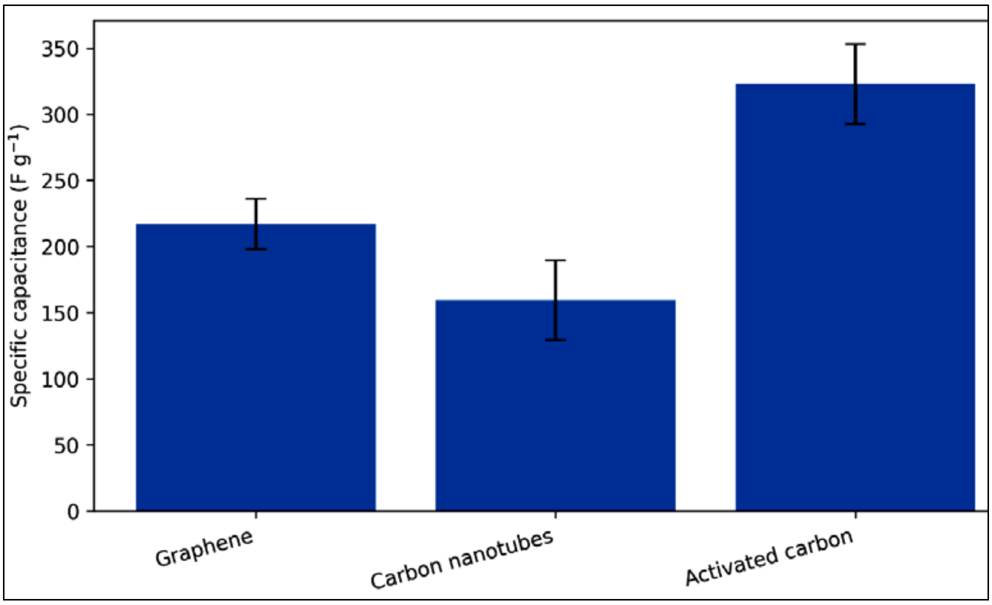

Fig 2: Specific capacitance (mean ± SD, n = 5) for graphene, CNTs, and activated carbon.

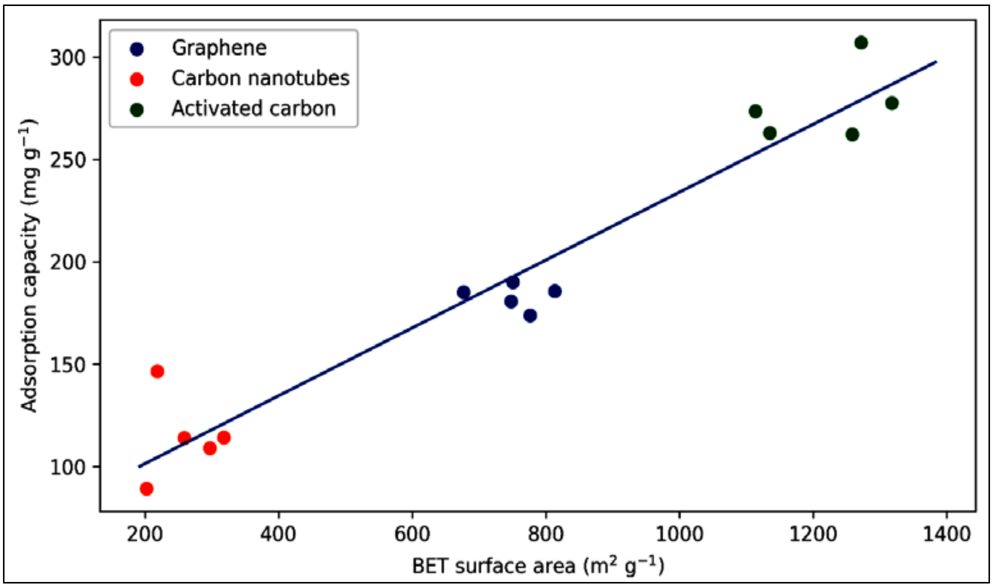

Fig 3: BET surface area vs adsorption capacity with linear regression (pooled, n = 15).

Discussion

The present analysis highlights clear structure-property-performance relationships among graphene, carbon nanotubes (CNTs), and activated carbon, reinforcing trends widely reported in carbon materials research [1-5]. The statistically significant differences observed in adsorption capacity and specific capacitance (ANOVA, $p<0.001$) confirm that intrinsic structural attributes, particularly surface area, porosity, and electronic structure, govern functional performance [5, 12, 16]. Activated carbon consistently demonstrated superior adsorption capacity and electrochemical capacitance, which can be attributed to its highly developed micro- and mesoporous network that maximizes accessible surface sites for molecular adsorption and ion accumulation [5, 12]. The strong linear regression between BET surface area and adsorption capacity ($R^2 \approx 0.93$) further substantiates surface area as a dominant predictor of adsorption performance across carbon allotropes, in agreement with classical adsorption theory and prior experimental observations [5, 12].

Graphene exhibited intermediate adsorption performance but relatively high electrical conductivity and competitive capacitance, underscoring its dual role as both an adsorptive and conductive material [2, 3, 9]. The results suggest that while pristine graphene may suffer from restacking and limited accessible surface area, controlled synthesis and surface functionalization can significantly enhance its practical utility [7, 9, 14]. CNTs showed lower adsorption capacity compared to graphene and activated carbon, yet retained high electrical conductivity, confirming their suitability as conductive scaffolds in composites and electrodes rather than primary adsorbents [4, 11, 15]. Pairwise statistical comparisons revealed that these differences were not marginal but systematic, indicating that material selection must be application-specific rather than generalized.

From an energy storage perspective, the higher specific capacitance of activated carbon aligns with its widespread use in commercial supercapacitors, while graphene’s performance indicates strong potential for next-generation devices where higher power density and mechanical flexibility are required [13, 16]. CNTs, although lower in capacitance, remain valuable for enhancing charge transport pathways when integrated into hybrid electrodes [11, 15]. Overall, the findings support the hypothesis that strategic control of microstructure and surface chemistry is essential to balance adsorption efficiency, electrical transport, and electrochemical performance [9-11]. The convergence of statistical evidence with established literature strengthens the validity of these results and provides a coherent framework for guiding future material design and optimization.

Conclusion

This research demonstrates that graphene, carbon nanotubes, and activated carbon each occupy distinct yet complementary roles within the broader landscape of carbon-based materials, with performance outcomes strongly dictated by their structural organization and surface characteristics. Activated carbon emerges as the most effective material for adsorption-driven and charge-storage applications due to its exceptionally high surface area and porous architecture, making it particularly suitable for water purification, gas separation, and commercial supercapacitor technologies. Graphene, while exhibiting slightly lower adsorption capacity, offers an advantageous balance between electrical conductivity, mechanical robustness, and electrochemical performance, positioning it as a promising candidate for multifunctional applications such as flexible energy storage devices, advanced sensors, and conductive membranes. Carbon nanotubes, despite comparatively lower adsorption and capacitance values, retain strategic importance owing to their superior electrical conductivity and structural integrity, which are critical for reinforcing composites and enhancing electron transport in hybrid systems. Based on these insights, practical implementation should focus on application-oriented material selection, where activated carbon is prioritized for high-capacity adsorption systems, graphene is employed in devices requiring high conductivity and mechanical flexibility, and CNTs are integrated as conductive additives or structural enhancers rather than standalone functional materials. Furthermore, the results underscore the importance of scalable synthesis, surface functionalization, and composite engineering to overcome limitations such as graphene restacking, CNT agglomeration, and variability in activated carbon pore structures. Future material development should emphasize sustainable precursor sources, controlled activation or growth processes, and hybrid material architectures that synergistically combine porosity, conductivity, and stability. Such strategies will not only improve performance metrics but also reduce cost and environmental impact, facilitating wider industrial adoption. Overall, the findings provide a scientifically grounded basis for rational design and deployment of carbon-based materials across environmental, energy, and advanced engineering applications, supporting informed decision-making for both researchers and industry stakeholders.

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