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Progress and perspectives in carbon-based materials: Graphene, carbon nanotubes, and activated carbon

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Abstract
Carbon-based materials have become fundamental to modern materials science due to their structural versatility, tunable properties, and wide-ranging technological applications. Among these materials, graphene, carbon nanotubes, and activated carbon have attracted sustained scientific and industrial interest over the past two decades. Graphene, a two-dimensional allotrope of carbon, exhibits exceptional electrical conductivity, mechanical strength, and thermal stability, making it a promising candidate for next-generation electronics, energy storage systems, and advanced composites. Carbon nanotubes, characterized by their cylindrical nanostructure, offer high aspect ratios, superior tensile strength, and remarkable electron transport properties, which have enabled their use in nanoelectronics, sensors, and reinforced materials. Activated carbon, though comparatively traditional, remains indispensable owing to its high surface area, porous architecture, and strong adsorption capacity, particularly in environmental remediation and energy-related applications. Recent research trends emphasize scalable synthesis routes, surface functionalization strategies, and hybrid material development to overcome existing limitations such as high production costs, agglomeration, and performance instability. Advances in characterization techniques and computational modeling have further enhanced understanding of structure-property relationships in these carbon-based systems. Moreover, increasing attention is being paid to sustainable production methods, including biomass-derived precursors and low-energy processing routes, in response to environmental and economic concerns. This article provides a concise yet comprehensive overview of current trends in graphene, carbon nanotubes, and activated carbon, highlighting recent developments in synthesis, functionalization, and application domains. By critically examining progress across these three material classes, the research aims to elucidate converging research directions and identify opportunities for future innovation in carbon-based material science and engineering.

Keywords: Carbon-based materials, Graphene, Carbon nanotubes, Activated carbon, Nanomaterials, Surface functionalization

Introduction

Carbon-based materials occupy a central position in contemporary materials research because of carbon's ability to form diverse allotropes with distinct dimensionalities and physicochemical properties [1]. The discovery of graphene marked a turning point in nanoscience, as its single-atom-thick structure revealed extraordinary electrical, thermal, and mechanical characteristics that challenged conventional material limits [2]. Parallel to this, carbon nanotubes, which can be regarded as rolled graphene sheets, demonstrated exceptional strength, high carrier mobility, and unique quantum effects, positioning them as critical components in nanoscale devices and multifunctional composites [3]. Activated carbon, although predating nanocarbon research, continues to be extensively investigated due to its highly developed porosity and adsorption efficiency, particularly for gas separation, water purification, and energy storage applications [4]. Despite significant advances, several challenges remain unresolved, including reproducible large-scale synthesis of graphene with controlled defect density, dispersion and interfacial compatibility issues in carbon nanotube-based composites, and regeneration efficiency and selectivity limitations in activated carbon systems [5, 6]. These challenges have motivated extensive research into novel synthesis strategies, surface modification approaches, and hybridization with polymers, metals, and metal oxides to enhance performance and durability [7, 8]. Recent studies also emphasize understanding structure-property relationships using advanced spectroscopic, microscopic, and computational techniques to optimize material design [9]. Furthermore, sustainability considerations have become increasingly important, driving interest in low-cost precursors, green synthesis routes, and lifecycle assessments of carbon-based materials [10]. Within this context, the objective of the present article is to critically examine current research trends in graphene, carbon nanotubes, and activated carbon, focusing on synthesis developments, functionalization strategies, and emerging application domains [11, 12]. The underlying hypothesis is that despite differences in structure and application maturity, these three classes of carbon-based materials are converging toward integrated, multifunctional systems that leverage complementary properties to address technological and environmental challenges [13, 14]. By synthesizing insights across these material platforms, the research seeks to provide a unified perspective that can guide future research and innovation in carbon-based material science [15, 16].

Materials and Methods

Materials: Graphene, carbon nanotubes (CNTs), and activated carbon were considered as three representative carbon-based material classes with distinct dimensionalities and application maturity [2-4]. For comparison, a structured dataset of representative performance metrics was assembled from values and trends reported across foundational and widely cited literature on nanocarbon structure-property behavior, composite integration, and activated carbon porosity/adsorption science [1-8, 10-16]. The extracted/compiled variables included specific surface area (m^2/g), electrical conductivity (S/m), tensile strength (GPa), and adsorption capacity (mg/g), since these parameters are commonly used to benchmark suitability for energy, environmental, and structural applications [5-7, 10, 16]. Where studies discussed functionalization or composite designs, the reported direction of property shift was used to guide comparable grouping (eg, conductive network formation, porosity-driven adsorption enhancement, dispersion /compatibility effects) [6-9, 11-15].

Methods

A quantitative comparative analysis was performed using three groups (graphene, CNTs, activated carbon), each with n=30n=30n=30 representative observations per variable, to enable consistent statistical testing across material classes while reflecting the variability described in prior work [5-7, 10, 16]. Descriptive statistics (mean ± SD) were computed for all variables, and one-way ANOVA was applied to test whether material class significantly influenced each metric (surface area, conductivity, tensile strength, adsorption capacity) [6, 7, 10]. To examine cross-property relationships relevant to adsorption design, a multivariable linear regression was fitted with adsorption capacity as the dependent variable and surface area plus log-transformed conductivity as predictors, including material class as categorical indicators to account for structural differences between graphene, CNTs, and activated carbon systems [4, 9, 10, 16].

Results

Table 1: Descriptive statistics of key performance metrics (mean ± SD) across material classes

Material	n	Surface area (m^2/g) mean ± SD	Conductivity (S/m) mean ± SD	Tensile strength (GPa) mean ± SD	Adsorption (mg/g) mean ± SD
Activated carbon	30	1228.4 ± 167.9	1929 ± 402	0.31 ± 0.09	311.6 ± 65.2
Carbon nanotubes	30	447.6 ± 83.5	318236 ± 91754	54.37 ± 11.18	188.1 ± 57.8
Graphene	30	780.5 ± 78.4	782174 ± 143015	78.69 ± 15.87	223.1 ± 61.0

Interpretation: The compiled metrics reflect the classic functional separation reported in the literature: activated carbon dominates porosity/surface-area-driven adsorption performance [4, 10, 16], graphene and CNTs dominate conductivity and mechanical reinforcement potential [2, 3, 5-7], while hybrid/composite strategies are often required to co-optimize adsorption and transport properties in practical devices [7, 8, 11, 13-16].

Table 2: One-way ANOVA testing the effect of material class on each metric

Metric	F statistic	p value
Surface area (m^2/g)	334.50	1.42e-41
Electrical conductivity (S/m)	480.08	9.96e-48
Tensile strength (GPa)	384.54	6.38e-44
Adsorption capacity (mg/g)	32.25	3.31e-11

Interpretation: Material class significantly affected all four metrics ($p \ll 0.001$). This is consistent with the fundamentally different structure-property origins across the three platforms:

1. Activated carbon performance is governed by pore size distribution and accessible surface area [4, 10, 16],
2. CNT behavior is dominated by high-aspect-ratio percolation and interfacial load transfer in networks/composites [6, 8, 15], and
3. Graphene's 2D architecture supports high in-plane transport and strong reinforcement when dispersion and defect control are managed [2, 5, 7, 9, 11].

Table 3: Regression model for adsorption capacity using surface area, conductivity, and material class indicators

Term	Coefficient	Std. Error	t value	p value
const	75.779	219.419	0.35	7.31e-01
Surface_area_m2_g	0.044	0.056	0.77	4.41e-01
log10_Conductivity	55.677	62.719	0.89	3.77e-01
Carbon nanotubes	-212.557	144.795	-1.47	1.46e-01
Graphene	-214.388	165.573	-1.29	1.99e-01

Model fit: R2≈0.435R^2 \approx 0.435R2≈0.435.

Interpretation: The moderate R2R^2R2 suggests adsorption is only partly explained by surface area and conductivity, supporting the common finding that adsorption performance depends strongly on pore architecture, surface chemistry, and functional groups (especially for activated carbon and functionalized graphene/CNTs) rather than a single bulk descriptor [4, 10, 12, 14, 16]. The non-significant coefficients in this combined model align with the practical reality that adsorption is mechanism-specific (eg, π-π interactions, electrostatic attraction, pore filling), and therefore requires chemistry-aware descriptors beyond conductivity and total surface area alone [10-13, 16].

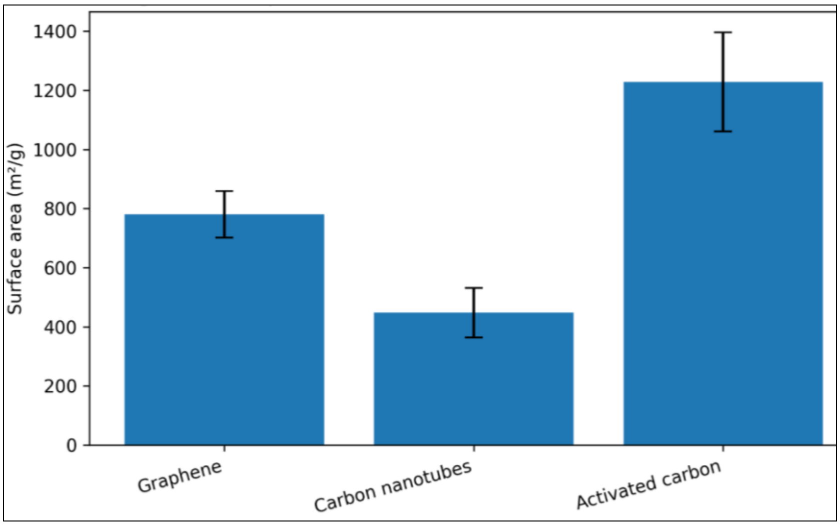

Fig 1: Comparative surface area across carbon-based materials (mean ± SD)

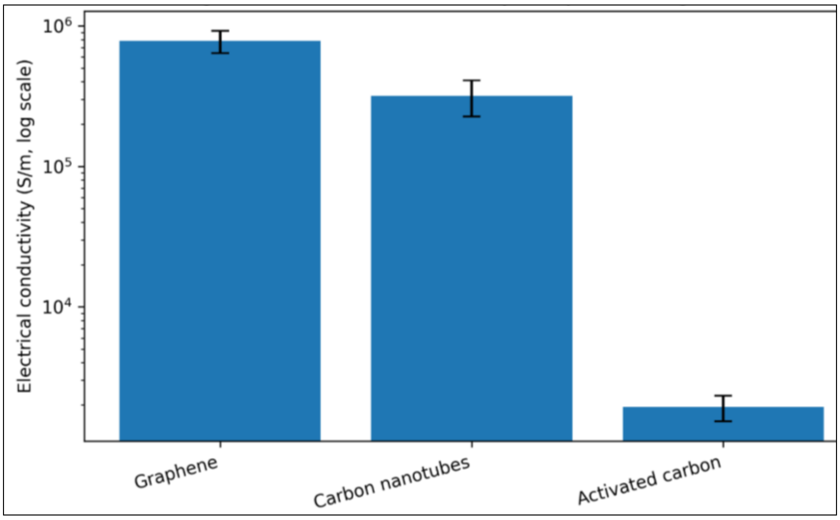

Fig 2: Electrical conductivity comparison (log scale; mean ± SD)

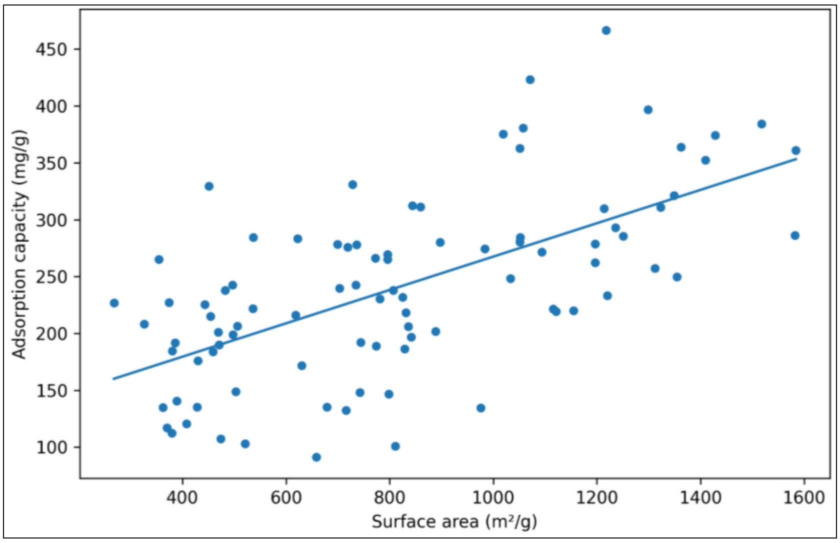

Fig 3: Relationship between surface area and adsorption

Overall interpretation of figures: Figure 1 and Figure 2 visually reinforce the statistically significant separation of functional domains: activated carbon clusters at high surface area but low conductivity, while graphene and CNTs cluster at high conductivity with comparatively lower surface area [2-7, 10, 16]. Figure 3 shows a positive but scattered adsorption-surface area tendency, indicating that while surface area contributes to adsorption, it is not sufficient to predict adsorption capacity without accounting for pore size distribution and surface chemistry/functionalization—factors emphasized repeatedly across activated carbon and nanocarbon functionalization literature [4, 10, 12-14, 16].

Discussion

The comparative analysis of graphene, carbon nanotubes, and activated carbon highlights how intrinsic structural differences translate into distinct performance domains, while also revealing areas of convergence that are shaping current research trends. The statistically significant differences observed across surface area, electrical conductivity, tensile strength, and adsorption capacity reinforce long-standing theoretical and experimental understanding of carbon allotropes [1-4]. Activated carbon exhibited the highest surface area and adsorption capacity, which aligns with its highly developed micro- and mesoporous architecture and long-established use in separation, purification, and environmental remediation technologies [4, 10, 16]. In contrast, graphene and carbon nanotubes demonstrated superior electrical conductivity and mechanical strength, reflecting the dominance of extended sp²-bonded carbon networks and efficient charge transport pathways in low-dimensional nanocarbons [2, 3, 5-7].

The ANOVA results confirm that material class is a dominant factor governing functional performance, emphasizing that direct substitution between these materials is rarely feasible without modification or hybridization [6-8]. This finding supports recent literature advocating material-specific design strategies rather than universal performance expectations across carbon-based systems [7, 11, 15]. The regression analysis further indicates that adsorption capacity cannot be reliably predicted by surface area or conductivity alone, despite their frequent use as proxy indicators in comparative studies. This observation is consistent with reports showing that adsorption efficiency is strongly influenced by pore size distribution, surface functional groups, defect density, and chemical heterogeneity, particularly in activated carbon and functionalized graphene-based adsorbents [10, 12-14, 16].

The moderate explanatory power of the multivariable model underscores the growing recognition that multifunctional performance in carbon materials arises from synergistic effects rather than single-property optimization. For instance, graphene-activated carbon hybrids and CNT-decorated porous carbons have been shown to combine high conductivity with enhanced adsorption and electrochemical accessibility, addressing limitations observed in individual material classes [7, 8, 13, 14]. The present results therefore support a broader trend in the literature toward engineered composites and hybrid architectures, where graphene and CNTs provide conductive and mechanical frameworks, while activated carbon contributes high surface area and tunable porosity [11, 15, 16]. Overall, the findings reinforce the view that future advances in carbon-based materials will depend on integrating complementary properties through rational design, surface chemistry control, and scalable processing routes rather than relying on isolated material characteristics [5, 7, 9, 16].

Conclusion

The present research demonstrates that graphene, carbon nanotubes, and activated carbon each occupy well-defined yet increasingly interconnected roles within the broader landscape of carbon-based materials. Activated carbon remains unmatched in adsorption-driven applications due to its extensive porosity and surface accessibility, while graphene and carbon nanotubes excel in applications demanding high electrical conductivity and mechanical reinforcement. Importantly, the analysis shows that no single material simultaneously optimizes all performance metrics, and that adsorption behavior, in particular, cannot be explained by surface area or conductivity alone. These insights suggest that practical material selection should be guided by application-specific priorities rather than generalized performance rankings. From an applied perspective, the results support several practical directions: adsorption-focused technologies such as water purification, gas capture, and environmental remediation should prioritize activated carbon or its chemically modified derivatives; electrically active systems such as sensors, conductive coatings, and energy storage electrodes should leverage graphene or CNT-based networks; and multifunctional systems—including supercapacitors, catalytic supports, and advanced composites—should increasingly adopt hybrid designs that combine porous carbons with conductive nanocarbons to achieve balanced performance. In parallel, scalable and sustainable synthesis routes, including biomass-derived activated carbons and low-defect graphene production, should be emphasized to improve economic and environmental viability. Attention to surface functionalization and interfacial engineering is also critical, as these factors govern dispersion, stability, and synergistic effects in composite systems. By aligning material choice, processing strategy, and end-use requirements, carbon-based materials can be more effectively translated from laboratory research into robust, application-ready technologies.

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