

# Dimensionality Effects on Carbon Allotropes: Comprehensive Literature Review

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**Abstract:** Carbon allotropes represent one of the most versatile families of materials in modern science, with their properties fundamentally shaped by their structural dimensionality. This literature review analyses how dimensionality—from zero-dimensional (0D) fullerenes to three-dimensional (3D) graphene networks—influences the physical and chemical properties of carbon nanomaterials and their technological applications. It is noted that 0D fullerenes exhibit pronounced quantum confinement effects and exceptional redox activity, 1D carbon nanotubes provide outstanding electrical conductivity and mechanical strength, 2D graphene offers unparalleled charge carrier mobility and surface area, while 3D structures enable enhanced mechanical stability and bandgap engineering. Tailored synthesis and functionalization techniques have enabled property optimization across dimensions, though challenges in scalability, uniformity, and defect control persist. The dimensionality of materials plays a pivotal role in determining the efficacy of energy storage systems, nanoelectronics devices, and sensing technologies, with the advent of hybrid materials that integrate multiple allotropes resulting in synergistic enhancements in performance. This review article emphasizes that dimensionality is a critical design criterion for the development of advanced carbon nanomaterials, while also illuminating the ongoing challenges associated with synthesis control, device integration, and long-term stability that must be surmounted to facilitate widespread technological implementation.

**Keywords:** Carbon Allotropes, Dimensionality, Fullerenes, Carbon Nanotubes, Graphene, Nanomaterials, Energy Storage, Nanoelectronics.

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## I. INTRODUCTION

### ➤ Background and Historical Context

The story of carbon allotropes is one of continuous discovery and innovation. Over the past three decades, the field has witnessed remarkable evolution—from the revolutionary discovery of fullerenes in the 1980s [1], through the synthesis of carbon nanotubes in the 1990s [2], to the isolation of graphene in 2004 [3]. Each milestone has shown materials with distinct dimensional architectures and exceptional properties that challenge our understanding of what carbon can achieve [15]. These materials display extraordinary electrical, mechanical, and thermal characteristics that have positioned them at the forefront of materials science research [5], [6], [10].

What makes carbon allotropes particularly attractive is their dimensional diversity. Unlike most elements that form a limited set of stable structures, carbon's unique bonding flexibility allows it to create stable forms ranging from zero-dimensional molecular cages to three-dimensional networks [15], [49]. This dimensional versatility translates directly into functional diversity, enabling applications that extend from

energy storage and flexible electronics to biosensing and environmental remediation [33], [42], [50]. The comprehensive research community has increasingly focused on harnessing these properties for sustainable technologies, recognizing that carbon nanomaterials could play a crucial role in addressing pressing energy and environmental challenges [31], [45].

### ➤ The Dimensionality Paradigm

Dimensionality serves as more than just a geometric form—it fundamentally governs the physical and chemical properties of carbon allotropes [5], [15]. Zero-dimensional structures like fullerenes and carbon quantum dots confine electrons in all three spatial dimensions, leading to discrete energy levels and quantum effects [14], [16]. One-dimensional carbon nanotubes restrict electron motion to a single axis, creating quasi-one-dimensional electronic systems with ballistic transport properties [9], [11]. Two-dimensional graphene allows electrons to move freely in plane, resulting in massless Dirac fermion behaviour and exceptional mobility [4], [5], [7]. Three-dimensional structures provide bulk-like properties with tunable porosity and mechanical robustness [22], [23], [24].

This dimensional hierarchy directly influences key material properties. Quantum confinement effects become increasingly pronounced as dimensionality decreases, affecting electronic band structure, optical absorption, and chemical reactivity [5], [14]. Surface-to-volume ratios increase intensely in lower-dimensional materials, enhancing their effectiveness in catalysis, sensing, and energy storage applications [32], [42], [43]. Mechanical properties also vary systematically with dimension—1D nanotubes exhibit extraordinary tensile strength along their axis [12], 2D graphene shows exceptional in-plane stiffness [6], while 3D structures provide isotropic mechanical stability [22], [23].

#### ➤ *Research Gap and Motivation*

Despite considerable investigation into specific carbon allotropes, our comprehension of how dimensional characteristics systematically influence physical and chemical properties and practical applications remains limited [45], [46]. Current scientific literature predominantly examines these materials separately, resulting in disconnected knowledge that impedes the creation of unified design frameworks [48]. Multiple important knowledge deficiencies continue to exist.

This field faces three primary obstacles. First, materials that merge or bridge different dimensions—such as carbon nanoscrolls displaying characteristics of both one-dimensional and two-dimensional systems, and three-dimensional hierarchical architectures built from two-dimensional sheets—have garnered substantially less scientific investigation compared to materials exhibiting single-dimensional attributes [46]. Second, controversy continues regarding optimal synthesis methodologies and property modification strategies, with different research groups reporting conflicting results concerning the effectiveness of various functionalization techniques [20], [45]. Third, the lack of integrated theoretical frameworks that systematically connect dimensional attributes to multiple functional characteristics constrains the capacity for deliberate design of sophisticated technological applications [48].

These knowledge gaps carry significant practical implications. In the absence of systematic knowledge about dimensional influences, scientists find it difficult to anticipate which allotrope or composite structure will deliver optimal performance for specific uses [33], [50]. Manufacturing processes that can be scaled up remain undeveloped for numerous promising materials, and obstacles in device implementation frequently block the translation of laboratory discoveries into commercially feasible products [41], [45], [50]. Resolving these constraints is crucial for progressing carbon nanomaterial technologies from basic science toward practical, real-world applications.

#### ➤ *Scope and Objectives*

This survey seeks to consolidate existing understanding of the ways in which dimensional characteristics shape the properties and uses of carbon-based materials, offering an integrated framework that connects basic scientific principles with technological advancement. The study systematically

investigates carbon nanomaterials categorized according to their dimensional properties: zero-dimensional structures (fullerenes, quantum dots) [1], [14], [16], one-dimensional forms (carbon nanotubes) [2], [9], [11], two-dimensional materials (graphene and related compounds) [3], [4], [6], and three-dimensional architectures (nanodiamonds, graphene foams) [22], [23], [24]. Within each classification, the analysis explores the relationships among structural features, electronic characteristics, and chemical properties, highlighting the role of dimensional limitations in controlling quantum confinement effects, hybridization configurations, and surface reactivity [5], [15].

The survey concentrates on three primary technological areas where dimensional effects demonstrate significant impact: energy storage and transformation [30], [31], [32], [36], [37], nanoelectronic applications [39], [40], [41], and detection systems [42], [43], [44]. The work examines fabrication and modification approaches customized for each dimensional category [17], [18], [19], [20], [21], evaluates their practical effectiveness in various applications, and identifies novel composite materials that integrate different carbon allotropes [25], [26], [27], [28], [29]. Through the synthesis of observations across all dimensional classifications, this survey delivers perspectives that guide material choice, production refinement, and component design, thereby facilitating the creation of sophisticated carbon-based technologies with improved performance and expandability.

## II. LITERATURE REVIEW

### A. *Dimensional Classification of Carbon Allotropes*

The dimensional classification of carbon allotropes provides a fundamental organizing principle for understanding their diverse properties and applications [5], [15], [49].

Structures with zero dimensions (0D) encompass fullerenes—spherical molecular cages like C<sub>60</sub> buckminsterfullerene [1]—along with carbon quantum dots. These materials restrict charge carriers across all three spatial axes, generating distinct molecular orbitals and significant quantum phenomena [14], [16]. The limited size of 0D configurations leads to elevated surface-to-volume ratios and distinctive electronic properties that substantially differ from bulk carbon forms [14], [15].

Carbon nanotubes (CNTs) represent one-dimensional (1D) cylindrical architectures created by wrapping graphene layers into continuous tubes [2]. Single-walled variants (SWCNTs) may exhibit metallic or semiconducting properties based on their chirality—the particular manner in which the graphene layer is wrapped—whereas multi-walled types (MWCNTs) comprise nested tubes held together by van der Waals forces between layers [9], [11], [13].

Graphene, a two-dimensional (2D) material, comprises a single-atom-thick layer of sp<sup>2</sup>-hybridized carbon atoms organized in honeycomb pattern [3]. This ultra-thin substance demonstrates remarkable characteristics including electron

mobility at room temperature, and mechanical robustness [4], [5], [6]. Modified forms of graphene—including graphene oxide, reduced graphene oxide, and chemically altered graphene—broaden the range of 2D carbon material properties through deliberate incorporation of functional groups and structural imperfections [19], [46], [49].

Three-dimensional (3D) configurations include both crystalline variants like diamond and nanodiamond, alongside porous frameworks such as 3D graphene foams and aerogels [22], [23], [24]. These substances offer bulk mechanical stability while frequently integrating nanoscale characteristics that amplify surface area and performance [22], [23].

Significantly, numerous investigations have identified hybrid dimensional architectures that challenge rigid categorical divisions [25], [26], [27], [28]. Carbon nanoscrolls—graphene layers wound into helical configurations—demonstrate properties falling between 1D and 2D systems. Nanocages and carbon onions constitute layered fullerene assemblies that merge 0D and 3D attributes [15]. These transitional structures frequently exhibit innovative properties unattainable with dimensionally pure allotropes, creating fresh opportunities for material engineering [25], [28], [29].

#### B. Structure-Property Relationships Across Dimensions

The relationship between dimensional architecture and material properties represents a central theme in carbon allotrope research [5], [15], [49].

##### ➤ *Electronic Properties*

Electrical characteristics show strong dimensional correlation. Zero-dimensional fullerenes display distinct molecular orbitals with defined energy gaps, making them efficient electron acceptors [14], [16]. Quantum confinement in 0D structures produces size-dependent optical properties with blue-shifted spectra in smaller particles [16]. One-dimensional carbon nanotubes present quasi-1D band configurations, with conducting types showing linear dispersion and semiconducting types exhibiting diameter-dependent bandgaps [9], [11], [13]. Two-dimensional graphene features charge carriers behaving as massless Dirac fermions, yielding exceptionally high mobility [4], [5], [7]. Three-dimensional carbon frameworks show bulk-like properties, though nanoscale features introduce quantum effects [22], [23]. Nanodiamonds exhibit wide bandgaps with surface states enabling quantum computing and bioimaging applications [15].

##### ➤ *Mechanical Properties*

Structural strength varies systematically with dimension. Carbon nanotubes possess exceptional axial tensile strength and elastic modulus, ranking among the strongest materials known, though with significant directional dependence [9], [10], [12]. Graphene demonstrates outstanding in-plane properties but remains vulnerable to out-of-plane deformation [6], [49]. Three-dimensional structures provide more uniform mechanical

stability, with 3D graphene foams combining high strength-to-weight ratios with structural resilience [22], [23], [24].

##### ➤ *Thermal Properties*

Heat transport reflects strong covalent bonding and low atomic mass. Graphene exhibits exceptional thermal conductivity, with individual nanotubes showing similarly high axial values [5], [6], [11]. However, transport across nanotube bundles or between graphene layers is limited by weak van der Waals forces, creating significant anisotropy [11], [13]. Three-dimensional structures show lower but more isotropic thermal conductivity [22], [23].

##### ➤ *Surface Chemistry*

Chemical properties are profoundly influenced by dimensionality through surface area and curvature effects. Zero-dimensional fullerenes present highly curved surfaces that strain  $sp^2$  bonding, increasing reactivity versus flat graphene [14], [15]. The high surface-to-volume ratios of 0D and 1D structures make them effective for catalysis and sensing [16], [42], [43]. Two-dimensional graphene offers maximum surface-to-volume ratio with every atom exposed, though its chemical inertness often requires functionalization for specific applications [19], [20], [46].

#### C. Synthesis and Functionalization Strategies

Carbon allotrope synthesis and functionalization have advanced significantly, exploring dimension-specific methods to enhance quality, scalability, and functionality [17], [18], [19], [20], [21].

Synthesis approaches differ by dimensionality. Zero-dimensional fullerenes use arc discharge, laser ablation, or combustion techniques, with emerging bottom-up organic synthesis enabling precise control over derivatives and quantum dots, though achieving uniform size and high purity remains difficult [1], [14], [15]. One-dimensional carbon nanotubes rely mainly on CVD with metal catalysts where process parameters influence structure, yet chirality-selective growth and defect-free purification are ongoing challenges [2], [13], [21]. Two-dimensional graphene production has progressed from mechanical exfoliation [3] to large-area CVD on metal substrates [17], [18], liquid-phase exfoliation for scalability [19], and graphene oxide reduction for easier processing, each with trade-offs in quality and cost [19], [46]. Three-dimensional structures like nanodiamonds and graphene foams use detonation, high-pressure methods, or template-directed CVD, with challenges in achieving uniform porosity and connectivity [22], [23], [24].

Functionalization enables property customization. Heteroatom doping (nitrogen, boron, sulfur, phosphorus) alters electronic properties and reactivity—nitrogen doping enhances electrocatalysis, while boron doping improves energy storage [20], [46]. Defect engineering creates catalytic active sites but may reduce conductivity, with techniques like plasma treatment offering controlled modification [20], [46]. Surface functionalization through covalent bonding introduces specific groups but disrupts the carbon network, whereas non-covalent methods preserve structure but offer weaker attachment [20], [29].

Persistent challenges include limited control over size, morphology, and purity—particularly for 0D and 3D materials—along with batch variability, scalability constraints, and cost-quality trade-offs that hinder commercialization [45], [46], [50]. Achieving atomic-level precision at viable costs remains critical research frontier [45], [48].

#### D. Applications in Energy Storage and Conversion

Carbon materials with different structural dimensions show significant potential for energy devices, with over 35 studies confirming that dimensionality impacts performance by affecting surface area, conductivity, ion movement, and structural integrity [30], [31], [32], [33].

For supercapacitors, zero-dimensional fullerenes and carbon quantum dots offer fast electron transfer and pseudocapacitive storage, delivering high power density and cycling stability despite limited energy capacity [14], [16], [32]. One-dimensional carbon nanotubes create efficient conductive networks and provide mechanical strength, achieving power densities above 100 kW/kg with excellent durability [10], [32], [38]. Two-dimensional graphene excels with its exceptional surface area (up to 2,630 m<sup>2</sup>/g) and conductivity, though sheet restacking during fabrication reduces performance—addressed through spacer insertion and 3D assembly techniques [30], [31], [32]. Three-dimensional graphene foams combine high surface area with structural robustness, achieving specific capacitances exceeding 400 F/g when hybridized with nanotubes or metal oxides [22], [23], [34], [35].

In battery applications, fullerenes serve as electron acceptors with limited capacity [14], [16], while nanotubes provide electrical connectivity and accommodate volume expansion in composite electrodes [36], [38]. Graphene-based anodes theoretically offer double the capacity of conventional graphite and serve as excellent matrices for silicon or metal oxide composites [36], [37]. Three-dimensional graphene frameworks maintain electrical connectivity during volume changes, substantially extending cycle life [22], [23], [36].

For fuel cells, nitrogen-doped nanotubes and graphene demonstrate catalytic activity for oxygen reduction, potentially replacing platinum catalysts [20], [33]. Three-dimensional porous structures further enhance performance by improving mass transport [22], [23], [33].

However, challenges remain: cost-effective scalable production, maintaining material uniformity, ensuring electrolyte compatibility, and preventing degradation during extended use [31], [33], [45]. Hybrid structures combining multiple dimensional forms offer a promising path forward [25], [26], [27], [28].

#### E. Nanoelectronics and Sensing Applications

Carbon allotropes with varying dimensionalities are crucial for advanced nanoelectronics and sensors, where their dimensional properties directly impact device performance [39], [40], [41], [42], [43].

Transistors and Logic Devices: One-dimensional carbon nanotubes (CNTs), especially semiconducting variants, excel in field-effect transistors with high on/off ratios and superior mobility, though challenges in synthesis and placement hinder commercialization [39], [40], [41]. Two-dimensional graphene offers exceptional mobility but lacks bandgap, limiting digital logic applications [40]. While bandgap engineering is possible, it often reduces mobility [40], [46]. Graphene performs better in high-frequency analog applications [39], [40]. Zero-dimensional quantum dots enable single-electron transistors and quantum computing through discrete energy levels, though requiring cryogenic conditions [16].

Photodetectors and Optoelectronics: Carbon quantum dots display size-tunable photoluminescence for LEDs, sensing, and photovoltaics [16]. CNTs provide wavelength-selective infrared detection with high responsivity and speed [39]. Graphene enables ultrafast broadband detection but with limited responsivity due to weak absorption [39], [40].

Chemical and Biological Sensors: Low-dimensional carbon materials' high surface-to-volume ratios enable sensitive detection [42], [43], [44]. Fullerenes and quantum dots act as fluorescent sensors responding to analytes via energy/charge transfer [16], [42]. CNTs detect gases at parts-per-billion levels through conductivity changes from molecular adsorption [42], [43]. Graphene sensors achieve single-molecule detection with ultimate surface exposure [42], [43]. Three-dimensional structures provide mechanical stability and improved analyte transport, while hybrid systems show synergistic performance enhancements [22], [23], [44].

#### F. Hybrid and Composite Materials

Combining carbon allotropes of different dimensions creates materials with synergistic properties that surpass individual components [25], [26], [27], [28], [29]. Each dimensional form offers unique advantages: fullerenes (0D) provide quantum effects [14], [16], nanotubes (1D) deliver axial conductivity [9], [10], graphene (2D) offers exceptional in-plane properties [5], [6], and 3D structures provide mechanical robustness [22], [23]. Hybridization overcomes individual limitations while enabling new functionalities [25], [28], [29].

##### ➤ Graphene-Nanotube Hybrids

These extensively studied combinations use nanotubes as spacers to prevent graphene restacking while enhancing conductivity and mechanical strength [25], [26], [27]. Applications in supercapacitors and batteries show superior performance, with nanotubes facilitating ion transport and graphene providing charge storage surface area [25], [27], [34]. Synthesis methods include direct CVD growth for strong covalent bonds or solution-based assembly for scalability [25], [28].

➤ *Fullerene-Graphene Composites*

Combining fullerenes' electron-accepting properties with graphene's high mobility improves photovoltaic efficiency and creates materials with tunable electronics [14], [16], [29]. Non-covalent  $\pi$ - $\pi$  interactions enable stable assembly, while covalent bonding offers stronger interfaces [29].

➤ *Three-Dimensional Hybrid Architectures*

3D graphene foams incorporating nanotubes exhibit enhanced mechanical and electrical properties [22], [23], [26], [27]. Carbon quantum dots integrated into 3D networks add photoluminescence and optical functionality for applications in light-emitting devices and sensors [16], [23], [44].

➤ *Non-Carbon Hybrids*

Carbon nanomaterials combined with metal oxides or polymers extend functionality [29], [34], [35]. Carbon provides conductivity and structural support while secondary phases contribute specific properties like catalytic activity or enhanced capacity [29], [33], [34].

### III. DISCUSSION

#### A. Dimensionality as a Design Parameter

Dimensionality serves as key design parameter in carbon allotropes, systematically affecting material properties and applications [5], [15], [49]. This framework enables researchers to select carbon structures based on specific needs: 0D for quantum effects [14], [16], 1D for axial strength and conductivity [9], [10], [12], 2D for surface area and mobility [4], [5], [6], and 3D for mechanical robustness [22], [23].

However, the dimensionality-performance relationship is complex. Real materials deviate from ideal behaviour due to defects, size effects, and environmental factors [45], [46]. For example, nanoscale graphene exhibits 0D quantum confinement, while nanotube bundles behave like 3D materials due to inter-tube interactions [11], [13].

Hybrid materials combining multiple dimensions represent the next evolution, accessing property combinations impossible in single-component systems [25], [26], [27], [28], [29]. The future lies in designing multi-dimensional architectures rather than optimizing individual allotropes, requiring new theoretical and characterization approaches to understand dimensional interactions [48].

#### B. Synthesis Challenges and Future Directions

Despite advances in carbon nanomaterial synthesis, major obstacles prevent commercialization [45], [50]. Key issues include precision control, scalability, and cost across all dimensions.

0D materials (fullerenes, quantum dots) suffer from broad size distributions and inconsistent surface chemistry, requiring tedious purification [14], [15], [16]. Atomic-level synthesis control remains a critical goal [45].

1D nanotubes lack chirality control, forcing expensive post-synthesis sorting to separate semiconducting from metallic types [13], [21], [41]. Emerging catalyst optimization and template-based "cloning" approaches show potential but need refinement [21], [45].

2D graphene production faces a quality-cost trade-off: CVD yields high-quality films but requires costly substrates and high temperatures [17], [18], while liquid exfoliation and graphene oxide reduction offer scalability at the expense of defects and smaller flake sizes [19], [46].

3D architectures struggle to simultaneously achieve uniform porosity, high surface area, and good connectivity [22], [23], [24]. Template methods provide control but increase complexity, while direct assembly sacrifices uniformity [23], [24].

#### C. From Fundamental Science to Technological Innovation

Bridging the gap between fundamental research and commercial applications requires addressing several key challenges [45], [50].

➤ *Integration & Manufacturing*

Laboratory success doesn't guarantee real-world viability. Incorporating carbon nanomaterials into existing production processes demands compatibility with standard fabrication methods [41], [50]. For example, integrating graphene into silicon electronics requires solving transfer, patterning, and contact issues [40], [41].

➤ *Economic Viability*

Performance gains must justify higher costs or prices must drop to competitive levels [45], [50]. High-value sectors (aerospace, medical devices) can absorb premium costs, while consumer electronics and energy storage need significant cost reductions [31], [50].

➤ *Durability & Reliability*

Long-term stability remains underexamined. Degradation from oxidation, contamination, or structural changes threatens applications requiring extended operation [45], [46]. Accelerated aging and field testing need more research focus.

➤ *Safety & Sustainability*

Potential toxicity, especially of nanotubes and fullerenes, requires thorough assessment [45]. Life cycle analysis, green synthesis, and recycling strategies are increasingly critical as production scales [45].

➤ *Standards & Quality Control*

Absent standardized characterization methods and quality metrics hinder cross-laboratory comparisons and consistent production [45], [47]. Industry-wide standards would accelerate commercialization [50].

➤ *Promising Near-Term Applications:*

Energy storage (enhanced electrodes) [30], [31], [36], [37], conductive additives/composites (significant property improvements at low concentrations) [29], [50], and sensors (leveraging exceptional surface properties) [42], [43], [44] show strong commercial potential.

*D. Limitations and Knowledge Gaps*

This review identifies critical knowledge gaps limiting progress in carbon nanomaterial research that should direct future investigations [45], [46], [48].

Molecular-level interfacial mechanisms in hybrid materials—including charge transfer, mechanical coupling, and chemical bonding—remain poorly understood despite documented macroscopic improvements [25], [28], [29]. In situ microscopy and spectroscopy techniques could provide essential insights [47].

Structure-property relationships for defects need systematic exploration [46]. Since real materials contain defects that significantly impact performance, predictive models incorporating realistic defect distributions would enhance materials design and quality standards [45], [46].

Intermediate structures like nanoscrolls and nanocages that bridge dimensional categories are underexplored yet may offer distinctive properties warranting systematic investigation [15], [46].

Comprehensive studies of environmental effects—temperature, humidity, chemicals, mechanical stress—on long-term performance are needed, as most characterization occurs under controlled conditions unlike real applications [45].

Scalable synthesis of quality materials remains challenging. Research must prioritize industrial-scale production barriers rather than solely laboratory demonstrations [45], [50].

Theoretical frameworks for hybrid materials lag experimental advances [48]. Multiscale computational approaches integrating quantum, molecular, and continuum methods are needed for realistic simulations [48].

Application-specific optimization deserves greater focus beyond fundamental characterization [33], [41], [44]. Collaboration between materials scientists and device engineers would accelerate practical implementation [41], [50].

## IV. CONCLUSION

This literature review synthesizes insights from over 40 studies examining how dimensionality determines the properties and applications of carbon allotropes across materials science, nanotechnology, energy, and electronics [5], [15], [49]. Dimensional architecture—from 0D fullerenes to 3D graphene networks—fundamentally governs electronic, mechanical, thermal, and chemical properties [5], [15].

Each dimensional class offers distinct advantages: 0D structures provide quantum confinement and molecular-scale functionality [14], [16]; 1D carbon nanotubes deliver exceptional conductivity and mechanical strength [9], [10], [12]; 2D graphene combines superior charge mobility, surface area, and flexibility [4], [5], [6]; 3D architectures enable mechanical robustness, tunable porosity, and bandgap engineering [22], [23], [24].

Advanced synthesis methods—including chemical vapor deposition [17], [18], liquid-phase exfoliation [19], heteroatom doping [20], and defect engineering [20], [46]—enable property customization. However, challenges remain in controlling morphology, purity, and defect distribution, while scalability and cost limit commercial adoption [45], [50].

Dimensional properties directly impact device performance. In energy storage, dimensionality affects surface area, conductivity, and ion transport, influencing energy density and cycle life [30], [31], [32], [36], [37]. In electronics, dimensional constraints determine electron mobility and switching speeds [39], [40], [41]. In sensors, surface-to-volume ratios govern detection limits and response times [42], [43], [44].

Hybrid materials combining multiple dimensional forms represent significant advancement, achieving synergistic enhancements through complementary strengths [25], [26], [27], [28], [29]. Graphene-nanotube composites and 3D architectures incorporating lower-dimensional components demonstrate improved charge transfer, stability, and multifunctionality [25], [27], [34].

Future priorities include developing scalable synthesis with atomic-level control, understanding interfacial phenomena in hybrids, addressing stability and environmental concerns, and establishing standardized characterization methods [45], [48], [50]. Success requires system-level design integrating multiple dimensions while addressing practical constraints of cost, scalability, and reliability [45], [50].

Dimensionality serves as a fundamental design parameter shaping carbon nanomaterial behavior [5], [15], [49]. Understanding dimensional effects enables rational material design for specific applications, positioning carbon-based technologies to address critical challenges in energy, electronics, and sustainability [31], [33], [45], [50].

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